FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

ANALYSIS OF METHODOLOGIES FOR VULNERABILITY AND RISK ASSESSMENT ON COASTAL AREAS

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To my Parents and Rui

A liberdade só existe

quando todos os nossos actos concordam com o nosso pensamento.

Agostinho da Silva

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RESUMO

Este trabalho, realizado no âmbito da defesa da dissertação para a obtenção do grau de mestre em Engenharia Civil da Faculdade de Engenharia da Universidade do Porto, incidiu sobre as diversas metodologias que existem para avaliar a vulnerabilidade e risco costeiro presentes nas zonas costeiras.

Nas últimas décadas e de forma generalizada mundialmente, a crescente presença de populações ao longo da orla costeira bem como os sucessivos eventos tempestuosos, tem alertado junto das entidades responsáveis pela gestão e planeamento costeiros para uma cada vez mais eficiente avaliação de vulnerabilidade e risco, como forma de auxilio com base em critérios científicos válidos.

A vulnerabilidade é entendida como as características e as circunstâncias da comunidade, sistema ou bem que o fazem susceptível aos efeitos prejudiciais de um *hazard*. Neste contexto, *hazard* remete para um fenómeno perigoso que pode causar perda de vida, impactos na saúde, danos em propriedades, perdas em meios de subsistência e serviços, interrupção socioeconómica e dano ambiental. Estes fenómenos perigosos são a erosão costeira, inundações e galgamentos.

No âmbito desta dissertação será estudada a vulnerabilidade das zonas costeiras face às acções do mar, nomeadamente, ao efeito das ondas, marés e correntes, bem como à subida do nível médio das águas do mar. Este último tem sido responsável pela criação e desenvolvimento da maior parte das metodologias de avaliação de vulnerabilidade e risco costeiro.

Desde o lançamento da "Common Methodology (CM)" pelo IPCC em 1991, um crescente número de abordagens em relação à vulnerabilidade costeira tem surgido e contribuído para o conhecimento avançado neste assunto. Eles variam desde guias básicos, técnicas e métodos de avaliação de vulnerabilidade e risco, métodos baseados em índices, métodos baseados em modelos dinâmicos e sistemas de apoio à decisão baseados em Sistemas de Informação Geográfica. Enquanto os primeiros três grupos de metodologias eram principalmente qualitativos e baseados no parecer do perito, os métodos baseados em modelos dinâmicos e sistemas de apoio à decisão foram desenvolvidos com recurso a modelos ambientais, bases de dados e ferramentas de avaliação que fornecem informação endereçando os campos físico, espacial, ecológico e económico.

Algumas características do Sistema de Apoio à Decisão desenvolvido no âmbito do Projecto THESEUS serão brevemente descritas.

PALAVRAS-CHAVE: Metodologias de análise, avaliação de vulnerabilidade costeira, classificação de risco, Sistemas de Apoio à Decisão.

ABSTRACT

This work, performed on the scope of the dissertation defence to achieve the Masters' degree on Civil Engineering from the Faculty of Engineering of University of Porto, focused on the several available methodologies for vulnerability and risk assessment on coastal areas.

In the last decades and generally worldwide, the growing presence of populations along the coast as well as the successive stormy events, has alerted authorities responsible for the management and coastal planning for an increasingly effective vulnerability and risk assessment, as a form of support based on valid scientific criteria.

The vulnerability is understood as the characteristics and circumstances of the community, or that are susceptible to the damaging effects of a hazard. In this context, hazard refers to a dangerous phenomenon which can cause loss of life, health impacts, damage to property, loss of livelihoods and services, socio-economic disruption and environmental damage. These dangerous phenomena are the coastal erosion, flooding and overtopping.

This dissertation will be focused on the vulnerability of coastal areas with regard to the actions of the sea, in particular, the effect of waves, tides and currents, as well as to rising sea level. The latter has been responsible for the creation and development of several methodologies for vulnerability and risk assessment on coastal areas.

Since the release of the Common Methodology, by the IPCC in 1991, a raising number of different approaches addressing coastal vulnerability has arisen and contributed to the advanced knowledge in this subject. They range from basic guidelines, techniques and methods for assessing vulnerability and risk, index-based methods, methods based on dynamic computer models and GIS-based Decision Support Systems. While the first three groups of methodologies were mainly qualitative and based on expert judgment, methods based on dynamic computer models and GIS- based DSS have been built with environmental models, databases and assessment tools, which provide information across physics, ecology, spatial sciences and economy field.

THESEUS Project, namely some features of the latest Decision Support System developed will be briefly described.

KEYWORDS: Methodologies of assessment, coastal vulnerability assessment, risk classification, Decision Support Systems.

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NOMENCLATURE

a_i - constants for each land use j

b_j - constants that express the expected period to restore economic activities

c - Wave celerity

D - Factor flood duration

D_{50} - Median beach grain size

De - Factor flood depth

h - Water depth corresponding to breaking conditions for H_s

H_s - Significant have height

$f_{2.5}$ - Friction factor dependent on the grain size

F_d - Flood duration

F_y - Flood depth

k - Constant governing the rate at which the shoreline approaches the equilibrium

L_0 - Wave length

P - Sediment pick-up rate

r - Marine water density

$R_{u2\%}$ - Wave run-up corresponding to the characteristic value of 2% exceeding probability

s - Relative density of sediments

S - Seasonality

S_{ed_y} - Sediment deposition depth

S_{ed_yd} - Sediment deposition and duration

U_w - Near bed velocity

t_b - Bottom shear stress due to waves

t_e - Critical bottom shear stress for erosion

T_r - Return Period

v_{ij} - Values of land uses in euro/m^2/year

W_s - Constant settling velocity of sediments

y(t) - Shoreline position at time t

y_{eq}(t) - Equilibrium shoreline position determined by forcing at time t

Z - Wave action

Z_m - Storm surge level

Z_r - Sea-level induced by climate change effects

η - Wave set-up

β - Beach slope

1
INTRODUCTION

1.1. MOTIVATION

Nowadays, coastal zones are largely considered worldwide as one of the best environments to live. By the other hand, the unplanned occupation of populations in these zones has exposed them to various types of extreme events. Therefore an analysis of the coastline environment is required, regarding both local sea characteristics and changes that the coast has been through since the human presence.

In the late decades, the number of studies concerning risk and vulnerability on coastal zones start to increase due mainly to the raising of awareness given by the media relating these destructive events. Despite the great recent developments and different methodologies developed, much is still to be discussed and clarified.

This master thesis intends to give some information concerning the content of methodologies for vulnerability and risk assessment in the coastal zones.

1.2. FRAMEWORK

Since remote times that populations have chosen coastal environment to settle and develop its life support activities. The number of people increased in the last decades and it is likely that such number will continue to grow while the environment quality is declining and local sea characteristics are reaching new values within smaller periods of time.

Many coastal areas and human activities are subject to increasing risks from natural and man-induced hazards such as flooding, coastal erosion and overtopping. This is particularly worrying in large coastal communities, where the presence of large amounts of people can lead to an emergency situation where the main disasters possible to happen are loss of lives, damaged infra-structures and disrupt transports and communications for days or weeks.

Since recent times that the study of this subject started. In the beginning, analysis were mainly qualitative due to the difficulty in obtaining data to incorporate in models and simulations. With the necessity for better information, namely quantitative, the different ways of classifying risk and vulnerability (Methodologies, Tools, Models, Decision Support Systems) started to extent the detail of the analysis including more advanced outputs.

By improving the understanding and awareness of the risks a coastal zone faces, decision makers, stakeholders and interested parties are in better position to agree on preventative measures to take and to prepare in ways to avoid the most severe consequences of natural and man-made hazards. The process of producing a risk assessment will also enable both public authorities and businesses, NGO's, and the general public to reach a common understanding of the risks face as a community.

The development of risk assessment and vulnerability analysis reveal to be of great value, giving contributions to the support of decision making and planning of coastal areas. Also, they contribute to ensure that policy decisions are prioritised in ways to address the most severe risks with the most appropriate prevention and preparedness measures.

1.3. OBJECTIVES

Following what was exposed in the previous point, the current master thesis was developed based on the following objectives. To introduce the whole subject of risk assessment it should be purposed a definition and discussion of the related concepts as well as make reference to what are the main vulnerability parameters to characterize the sensitivity of coastal strip considered.

Another fundamental objective of this thesis is to make reference to the existing methodologies, models, tools and Decision Support Systems, responsible for the vulnerability analysis, risk evaluation and adaptation measures. They are divided in groups according to the scale of application, level of detail, type of outputs and qualitative/quantitative information.

As previously mentioned, the need for risk assessment arises from the presence of populations at an hazard zone, which has suffered from at least one resulting phenomena of ocean dynamics, sea waves, tides and currents or consequence of sea-level rise.

Flooding, coastal erosion and overtopping are the most frequent hazards that coastal zones have to deal with. A description and characterization of them are of utmost importance for the necessary understand of how their consequences should be reduced. It is important to characterize and to frame in the investigation and research process for plausible planning strategies and defence options.

Risk assessment of coastal areas due to extreme events has been developing since the 80's. The main reason is the fact that some knowledge is necessary to inform coastal communities and to take part of the scientific content in political and planning measures.

To be able to classify the risk that a given coastal area faces, there are some steps that should be done before. To evaluate the sensitivity of the coast, a vulnerability analysis turns to be the first step.

1.4. THESIS STRUCTURE AND CHAPTERS DESCRIPTION

This thesis is divided into 3 core chapters, described as follows. After this first introductory chapter, the second chapter is intended to introduce the main reasons behind the concept of risks and vulnerability assessments by making reference to the causes and what motivates this type of research. In this context, causes can be understood as the things that asks for risk and vulnerability assessments, like the presence of populations along the coast or the dangerous phenomena that make them vulnerable. These dangerous phenomena are the coastal hazards, namely coastal erosion, dune or bluff, flooding and overtopping.

The chapter presents the basic terminology when dealing with the risk and vulnerabilities assessment, lists some examples of vulnerability parameters and their classification, based on previously analysis of worldwide study cases.

Chapter 2 also introduces the whole concept of vulnerability of coastal zones, making a reference to the parameters or indicators most used to assess the sensitivity or exposure of that coastal zone.

In Chapter 3 is gathered information based on the state of art and reviewed literature. It stars to making a brief introduction to the different types of approaches that the process of risk and vulnerability classification has.

The fourth chapter introduces the new GIS-based Decision Support System, recently developed by a EU-funded project that provides an integrated project within coastal risk assessment and mitigation.

It was chosen due to its features, namely the integrated methodology for planning sustainable defence strategies for the management of coastal erosion and flooding, addressing technical, social, political and environmental aspects.

THESEUS will be described in this chapter, regarding the main assumptions and considerations made by its authors while developing the different components of the Decision Support System, namely the modelling tool.

The fifth chapter will include the conclusions of this present work, focusing on some particular features of some previously referred methodologies for vulnerability and risk assessment. Some future improvements that developers should address will also be pointed in the current chapter.

2
COASTAL ZONES: VULNERABILITY, RISK AND OTHER CONCEPTS

2.1. INTRODUCTION

Coastal zones are part of nature fascination. Since remote times in human history that populations have chosen the coastal environment as one of the best places to live. For this reason, vulnerability and risk assessment pretends to give answers to policy-making authorities in order to protect populations by showing results of the analysis done.

Ocean dynamics and sea-level rise are subjects that interest to authorities and stakeholders in order to provide an efficient management of the coastal zone. For these reasons, a specific definition, or at least with a common understanding, should be establish in order to make clear to all the possible interventions.

Concerns about coastal hazards and disasters have become linked closely to risk and vulnerability. Hazards, risks, disasters, and vulnerabilities have each one slightly different concerns, but the terms are occasionally used interchangeably (Cutter, 2002). For this reason, developing a wide knowledge in this subject requires a fundamental understanding of these concepts and their relations.

This chapter introduces the general process of vulnerability and risk analysis by making a brief description of all the concepts and meanings that should be understood in order to create a bright image of what involves a risk assessment process.

Furthermore, a description of which parameters are considered when developing the assessment of vulnerabilities and risks will be made, based on the assumptions and considerations taken by (Coelho, 2005, Gornitz *et al.*, 1997, Thieler and Hammar-Klose, 1999).

The analysis and classification of vulnerability is fundamental to characterize the sensitivity of a given stretch of a coastal zone, in particular to all the maritime actions which result in frequent overtopping, flooding and coastal erosion. Such actions undermine the socio-economic activities located on the coast, often leading to interruptions for maintenance and rehabilitation of defence structures (Gornitz *et al.*, 1997).

2.2. COASTAL ZONES AND POPULATION: PRESENT AND FUTURE

Since remote times in history that populations has chosen the coastal environmental for settle, develop economic and commercial activities, establish a way of communication and for recreational and touristic purposes.

A significant and increasing part of the EU population lives in the coast. Some reports from studies carried out by international entities related with the quantification of coastal occupation, state the following data:

- Approximately half the EU population lives 50 km or less from the coast (ESTAT, 2009);
- Approximately 19% of the EU population (86 million people) lives within a 10 km coastal strip (EEA, 2006);

Collectively, this two aspects placing growing demands on coastal resources as well as increasing people's exposure to coastal hazards (Sterr *et al.*, 2000).

As evidenced by these references, the coastal occupation has resulted in the current society many concerns, due mainly to the presence of a high number of people. Coastal zones are places under high habitation pressure, including a wide number of often conflicting human and socio-economic activities occurring there. Figure 2.1 shows an example of a highly pressurized coast.

Figure 2.1 - Miami Downtown and Miami Beach, Florida, United States of America

The widely group of resources that coastal zones offer to populations, and its increasable urbanisation, tourist facilities, recreational activities and others, has demanded a growing worry to policy-makers and other entities that deal with this multi-hazard scenario.

Further that, there are studies which predict that is likely that such numbers of population will increase in the future (Ramieri *et al.*, 2011).

The human presence along the coast and its expansion evidenced worldwide, "asks" for the creation and development of risk assessment methodologies, ranging from tools and techniques of vulnerability analysis to more complex decision support systems, to give solutions to coastal communities as well as formulate an agreed basis for politics in planning options.

2.3. Coastal Hazards: Erosion, Flooding and Overtopping

Coastal hazards are the physical phenomena that expose a coastal area to risk of loss of life, property damage and environmental degradation. The major coastal hazards that coastal communities face are flooding, wave impacts and subsequent overtopping, and erosion resulting from storms.

Figure 2.2 - Storm waves breaking over the breakwater of Porthcawl, Wales, United Kingdom

Events like storm waves, flooding and erosion share similar damage mechanisms. Damage can occur during these events including high water level, strong currents, impact forces, and erosion.

A list of the consequences of these actions are presented below (Cutter, 2002):

- loss of human lives;
- property losses ranging from damage to complete destruction;
- environmental damage;
- shoreline reconfiguration;
- interruptions of routine community, and
- short- and long-term disruptions of economic activity.

Table 2.1 provides some characteristics of the erosion event and the possible influences resulting from climate change (Cutter, 2002).

Table 2.1: Characteristics of Erosion Events (Ewing, 2014)

Event type	Pre event	Event	Post-event Condition	Influences from Climate change
Erosion	Beach, dune, and bluff erosion often driven by storm events and large waves.	Rapid drop in beach elevation as sand is carried offshore.	Initial beach recovery within days to weeks, often not to pre-event conditions. Longer term beach and dune recovery can be a season to several years.	Increased inland migration of beach face due to sea-level rise and greater inundation.
	Bluff erosion can be preceded by cracks in upper bluff or landslide conditions.	Retreat of bluff bringing its sediments to the beach or nearshore.	Long-term erosion of beach and dune is possible. Bluff retreat irreversible within foreseeable time periods.	Increased inland retreat of dunes and bluffs due to adjustment in beach position and increased frequency and power of wave attack due to higher water levels from sea-level rise.

The characteristics of erosion events will influence options that communities consider for resilience. Here, resilience means the ability of a community or system to maintain functionality during events. The event characteristics represent the safety and protection options that could minimize consequences. The post-event characteristics indicate the options and timing for response and recovery, and influences due to climate change indicate suitability of using historic trends and prior disasters to future events (Ewing, 2014).

As previously mentioned, coastal erosion is a variable phenomenon, whether in time and space. It is important to understand the causes which may lead to different types of destruction, and to search for solutions whether the place is highly inhabited or it presents only ecological values. Sometimes it is possible to link some wave behaviour with erosion phenomenon.

Beach erosion can be the seasonal change or the long-term changes in the beach shoreline position. Seasonal changes are often strongly associated with the wave climate, where the higher energy storm waves and "winter" waves pull sand off the beach and the milder, "summer" waves bring sand back onto the beach. Sea-level rise will increase beach erosion and/or the landward retreat of the beach. Long-term beach erosion, resulting from wave action, storms, and changes in sediment supplies, can result in a chronic narrowing or landward migration of the shoreline. Sometimes, this may be accompanied by the inland relocation of the back shore, or, if the back shore position is fixed, it will result in an overall narrowing of the upper beach zone (Ewing, 2014)

The direct threats from both seasonal and long-term beach erosion are that inland structures may be undermined, a loss of foundation support can occur and the stability of the buildings, roadways, pipelines, or other developments supported by the beach will be at risk (Ewing, 2014).

The loss of beach width will also reduce buffering and dissipation of wave energy and flood waters in front of inland development. So, an indirect impact from beach erosion can be the increased damage to inland development from wave attack and flooding.

Dune erosion also results from wave energy dissipation. In a beach-dune system there is often an exchange of sand between the beach and dunes. When there is excess of beach sand, wind will carry it into the dunes resulting in dune growth. But, as waves erode the beach area, the back dune system can serve as a sand storage system, providing additional sand to the beach and nearshore areas during storm events. The cycle of sand exchange between the beach and the dune, like seasonal beach change is rapid in the dune erosion phase and slower in the dune recharge phase.

The transfer of sand from the dunes to the beach can occur in a few hours during a storm, but the rebuilding of the dune may take several years, if there is enough sediment in the littoral cell. If new supplies of sediment are not available in the area, the beach-system dune may become a one-way conveyance of sand, where the dunes rarely experience any accretion (Ewing, 2014).(Ewing, 2014)(Ewing 2014)(Ewing 2014)(Ewing 2014)(Ewing 2014)

Dune erosion, Figure 2.3, like beach erosion, can cause inland structures to be undermined or lose foundation support. The loss of dune width will also reduce the buffering and dissipation of wave energy, causing indirect impacts similar to those associated with beach erosion. And, a migrating dune system can move inland, sand blasting and covering inland development or overrunning roads, filling drainage areas.

Figure 2.3 - Dune erosion in Long Beach Island, New Jersey, United States of America

Coastal bluff erosion, as shown in Figure 2.4, can result from wave attack as well as geologic faulting, landslides, and groundwater soil saturation. Coastal bluff erosion is not considered to be reversible because can accrete from seismic activity over thousands of years, but bluffs will not rebuild within human-scale time periods.

Bluff erosion can occur as a gradual, chronic loss of bluff material, or it can be rapid and episodic. Most of bluffs experience both chronic and episodic erosion, although the episodic events are the ones most people notice and remember.

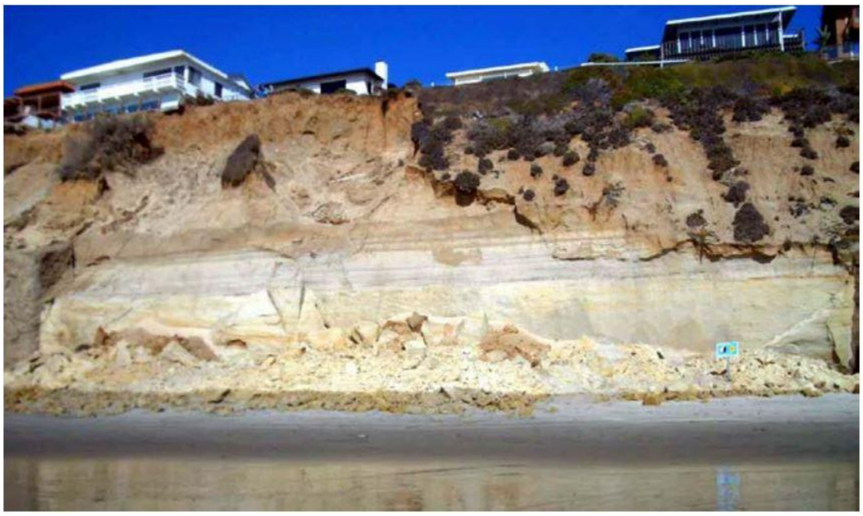


Figure 2.4 - Costal bluff retreat, Solana Beach, California, United States of America (Ewing, 2014)

Flick *et al.*, (2012) have defined inundation "as the process of a dry area being permanently drowned or submerged" and it can result from long-term erosion, land subsidence and sea-level rise. In contrast, flooding occurs when "dry areas become wet temporarily - either periodically or episodically" (Flick *et al.*, 2012).

Storm waves can cause flooding and inundation. The time and extent of the flooding will depend of the specific event, bathymetry, overland topography, flooding barriers, and inland structures. If erosion has also occurred, these conditions can exacerbate the flooding impacts, as well as sea-level rise can also exacerbate flooding.

The direct threats from inundation are the permanent wetting of dry land, losses of agricultural lands and conversion of intertidal lands to subtidal. Flooding can temporarily close down many infra-structures, especially if the water remains for more than a few hours.

Wave impacts come during storm events when wave energy is not fully dissipated in offshore breaking and run-up. Wave overtopping phenomenon is another problem that the coastal populations face. It occurs when waves meet a submerged reef of structure, but also when waves meet an emerged reef or structure lower than the approximate wave height.

The origin of wave overtopping is wide and it include: astronomic and meteorological tides; storms (sea ripple); sea-level rise; destruction of dune systems and dredging works. Coastal flooding is usually preceded by overtopping of the defences or barriers. During storms, waves exceed the height of the existing defences and the flow of water hit the infra-structures located on the coast.

It is necessary to analyse the consequences of the phenomenon, regarding the territory losses and its damage on assets, infra-structures and buildings.

Climate change and sea-level rise provide additional motivation for most coastal communities to understand their hazard exposure. Sea-level rise alone will, with certainty, worsen the consequences of storm flooding, wave impacts, and erosion simply by exposing coastal areas more frequently and more extensively to these hazards (Ewing, 2014).

Projections indicate that sea level will continue to rise, possibly rising by an addition of 1.5 to 2 m by 2100 (Figure 2.8).

The main drivers of changing sea level are thermal expansion of existing ocean water and increases in the amount of water in the ocean due to melting of land-based glaciers, ice sheets, and human-caused changes in groundwater pumping and water storage (Chao *et al.*, 2008, Konikow, 2011, Wada *et al.*, 2010).

Except for the human-caused changes in surface water, the sea level drivers are connected with global temperature that is rising due to increased emissions of carbon dioxide and other greenhouse gases (Ewing, 2014).

The Intergovernmental Panel on Climate Change (IPCC) has become one of the main international forums for discussion of climate and sea-level rise. It has used scenarios to develop likely future climate conditions. Their initial assessments were based upon assumptions of population growth, technological growth and expansion, and resulting greenhouse gas emission scenarios.

The IPCC reports provide likely changes to sea level, along with many other climate aspects, based on three scenarios. Under the most optimistic scenarios for emissions and radiative forcing, sea level rise could slow and stabilize toward the end of the 21st century, but under most scenarios, sea level is expected to continue rising well into the 22nd century.

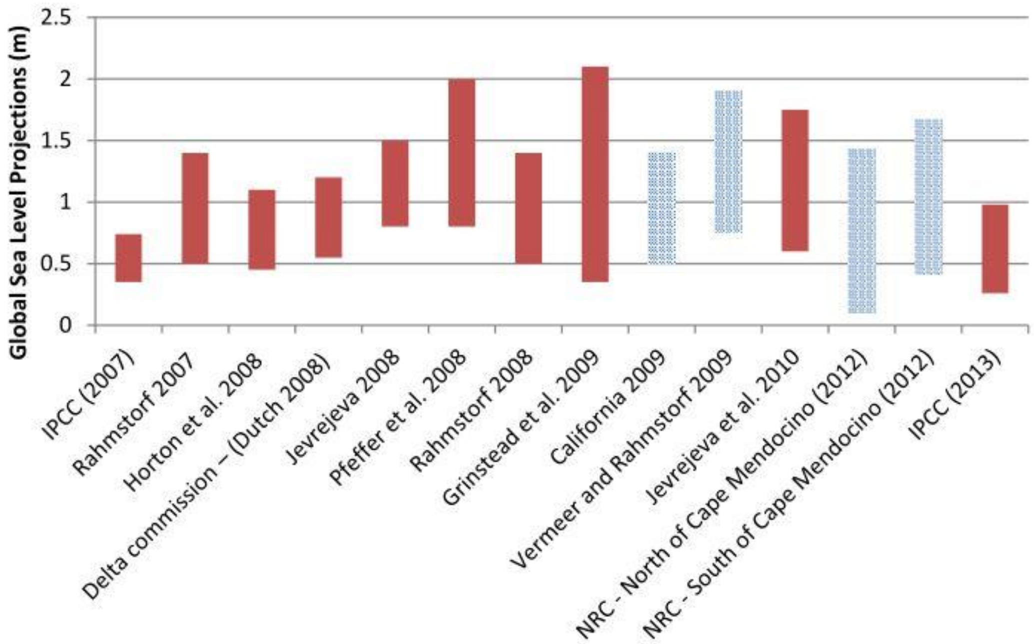


Figure 2.5 - Various 2100 Global and Regional Sea Level Projections, (California Coastal Commission, Draft Sea Level Rise Guidance)

Future sea-level is uncertain being some of it associated with the models and with ice dynamics, and some uncertainty is associated with future emissions. Research and better science can help reduce some of this uncertainty, but due to human actions, a large uncertainty will remain in future water level projections.

As shown in Figure 2.9, water level is on the basis for inundation, flooding, currents, and wave impacts. Being future water level based on projections, it leads to uncertainties about the future impacts of those hazards.

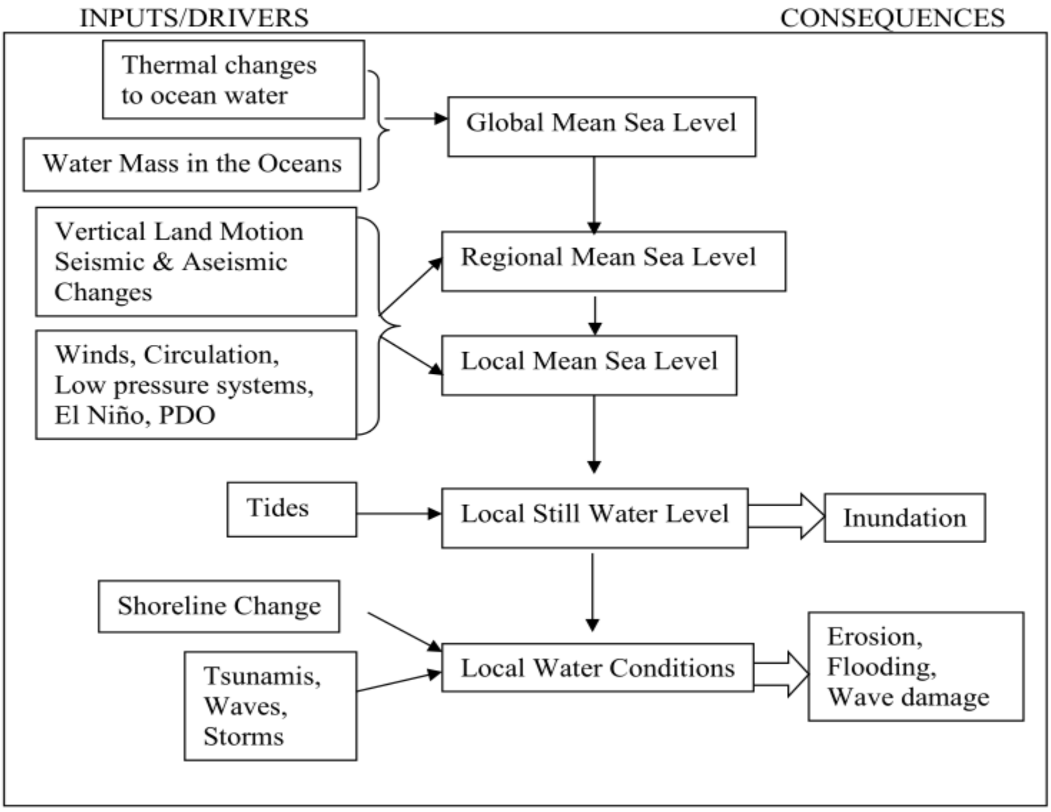


Figure 2.6 - Trends between Water Levels and Coastal Consequences. Modified by R. Flick and L. Ewing (Ewing, 2014)

Water level uncertainty combines with uncertainties concerning other climatic conditions, including changes in hurricane and tropical storm frequency and intensity, rainfall and flooding events, erosion, waves, El Niño frequency and intensity.

The result is uncertainty in almost everything used as input for long-term coastal engineering design. Engineered structures will continue to be part of the coastal protection, but the uncertainties in future conditions add to the need for resilient coastal protection that can adapt to unanticipated events and recover from events that exceed the design conditions.

2.4. VULNERABILITY

2.4.1. DEFINITION OF TERMS AND RELATED CONCEPTS

Achieving a common terminology of vulnerability and related concepts remains a challenge. It is vastly recognized that terms related with this subject are quite diverse, depending on the author, the study that apply them and context, often leading to multiple definitions, sometimes antagonistic.

Many scientists, researchers and practitioners have developed specific terminology for vulnerability and risk assessments. This terminology differs significantly between the various disciplines.

It is not fully intention of this thesis to purpose a new, bright definition of these terms, clarify or to compare different definitions of the current issue. However it is necessary to show some points of view that could differ in specific concerns. One of the most important sources of this kind of subject is the International Organisation for Standardisation (ISO) which has developed some international standard definitions related with this subject.

The sources from ISO are:

ISO 31000: Risk management - Principles and Guidelines; was released in 2009 and provides principles and generic guidelines on risk management. It can be used by any public, private or community enterprise, association, group or individual. It is not specific to any industry or sector;

ISO 31010: Risk management - Risk Assessment Techniques; is a supporting standard for ISO 31000 and provides guidance on selection and application of systematic techniques for risk assessment;

ISO Guide 73: Risk management – Vocabulary; provides the definitions of generic terms related to risk management.

For a common understanding of the following chapters, risk assessment definition of terms will be used as EU guidelines, Risk Assessment and Mapping Guidelines for Disaster Management, which are listed below:

Hazard - is a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.

Exposure - People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (ISDR, 2009).

Vulnerability - The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (ISDR, 2009). In probabilistic/quantitative risk assessments the term vulnerability expresses the part or percentage of Exposure that is likely to be lost due to a certain hazard.

Resilience - The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (ISDR, 2009).

Risk - is a combination of the consequences of an event (hazard) and the associated likelihood/probability of its occurrence (ISO, 2009).

Risk assessment - is the overall process of risk identification, risk analysis, and risk evaluation (ISO, 2009).

Risk identification - The process of finding, recognizing and describing risks (ISO, 2009).

Risk analysis - The process to comprehend the nature of risk and to determine the level of risk (ISO, 2009).

Risk evaluation - is the process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable (ISO, 2009).

Risk criteria - The terms of reference against which the significance of a risk is evaluated (ISO, 2009).

Consequences - The negative effects of a disaster expressed in terms of human impacts, economic and environmental impacts, and political/social impacts (ISO, 2009).

Human impacts - Defined as the quantitative measurement of the following factors: number of deaths, number of severely injured or ill people, and number of permanently displaced people.

Economic and environmental impacts - Sum of the costs of cure or healthcare, cost of immediate or longer-term emergency measures, costs of restoration of buildings, public transport systems and infrastructure, property, cultural heritage, etc., costs of environmental restoration and other environmental costs (or environmental damage), costs of disruption of economic activity, value of insurance pay-outs, indirect costs on the economy, indirect social costs, and other direct and indirect costs, as relevant.

Political and social impacts - Usually rated on a semi-quantitative scale and may include categories such as public outrage and anxiety, encroachment of the territory, violation of the democratic system, and social psychological impact, impact on public order and safety, political implications, psychological implications, and damage to cultural assets, and other factors considered important which cannot be measured in single units, such as certain environmental damage.

Single-risk assessments - determine the singular risk (i.e. likelihood and consequences) of one particular hazard (e.g. flood) or one particular type of hazard (e.g. flooding) occurring in a particular geographic area during a given period of time.

Multi-risk assessments - determine the total risk from several hazards either occurring at the same time or shortly following each other, because they are dependent from one another or because they are caused by the same triggering event or hazard; or merely threatening the same elements at risk (vulnerable/ exposed elements) without chronological coincidence.

Hazard assessments - determine the probability of occurrence of a certain hazard with certain intensity.

Hazard map - map that portrays levels of probability of a hazard occurring across a geographical area. Such maps can focus on one hazard only or include several types of hazards (multi-hazard map).

A single type of hazard map is shown in Figure 2.10, where the lines of equal probability represent the likelihood of loss due to erosion event.

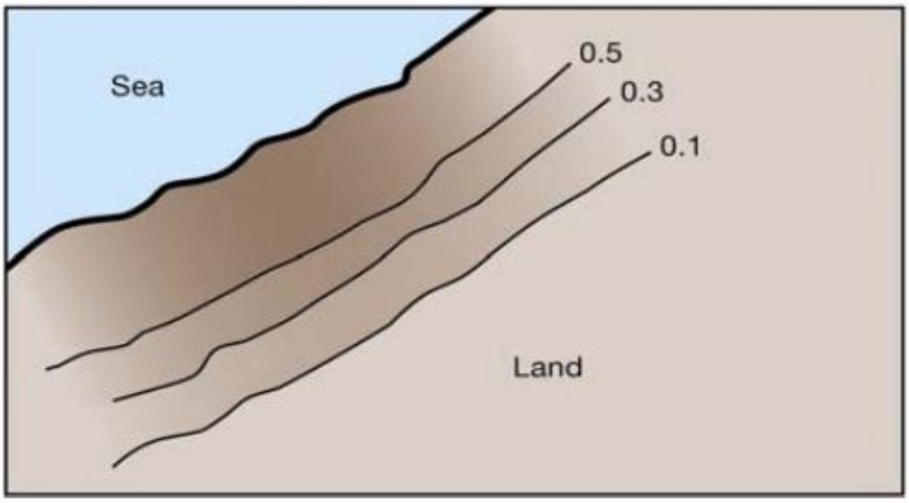


Figure 2.7 - Hazard Map portraying lines of equal probability of losses due to erosion (Halcrow Group, 2007)

Risk map- Map that portrays levels of risk across a geographical area. Such maps can focus on one risk only or include different types of risks.

An example of a risk map of coastal erosion is given on Figure 2.11.

Risk scenario- Representation of one single-risk or multi-risk situation leading to significant impacts, selected for the purpose of assessing in more detail a particular type of risk for which it is representative, or constitutes an informative example or illustration.

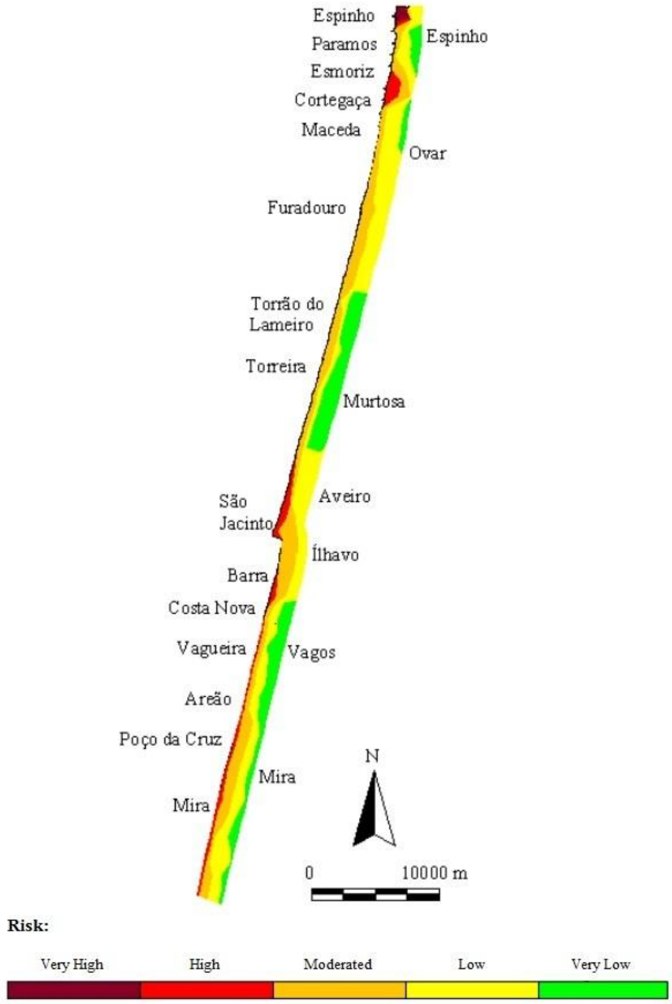


Figure 2.8 - Risk map of coastal erosion (Pereira and Coelho, 2013)

2.4.2. Vulnerability on Coastal Zones

Vulnerability on coastal zones has also a variety of definitions. In the development of this research, vulnerability is an important feature for an efficient methodology in assessing the potential negative effects on the coastline, due to sea actions.

Vulnerability is defined according to the United Nations International Strategy for Disasters Reduction as the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.

There are many aspects of vulnerability, arising from various physical, social, economic, and environmental factors. Examples may include poor design and construction of buildings, inadequate protection of assets, lack of public information and awareness, limited official recognition of risks and preparedness measures, and disregard for wise environmental management. Vulnerability varies significantly within a community and over time. This definition identifies vulnerability as a characteristic of the element of interest (community, system or asset) which is independent of its exposure. However, the word vulnerability is often used more broadly to include the element's exposure.

With regard to coastal areas, analysis of target vulnerability is in relation to the action of sea wave sin particular phenomena resulting from storms that will have a variable impact on both spatial natures, whether temporal .Overtopping, flood and coastal erosion are the most evidence phenomena resulting from sea waves, tides and currents.

There are also several types of vulnerability that coastal areas shall be exposed (Coelho, 2005):

- Vulnerability of coastal areas due to spills and discharges of pollutants, as it is a problem for other subjects, namely the chemical assessment of coastal and ocean engineering;
- Vulnerability of the coastal zone associated with navigation as it is a problem related with coastal management and planning;
- Vulnerability of the coastal areas due to seismic actions;
- Vulnerability of the coastal zone due to the exploitation of water resources.

The defence costs in coastal regions around the world are increasing and we need to evaluate and understand the phenomena involved, in order to consider carrying out interventions on the coastline over longer time horizons.

The vulnerability analysis, to a certain range of the coastal zone is a time consuming process and involves the selection of innumerable parameters. It is based on the selection and weighting factors and their evaluation is effected based on the degree of vulnerability they present. It may be necessary to incorporate vulnerability parameters in a hydro-morphological modelling software that enables the coast projections for different time horizons considering different scenarios of natural and anthropogenic actions (Coelho, 2005).

The study of vulnerabilities requires a lot of information and a multi-disciplinary approach that should cover the engineering, environment, socio-economic and political fields (Nicholls, 1998). The first key step to try to reduce the potential for damage is to determine and map the risks.

Other authors, Blaikie *et al.* (2014) and Smith (2013) have also shown some other ways of describing these concepts. One overall meaning was adopted related with the vulnerability of the coastal zones:

- It can be understood as a function of the system's ability to cope with stress and shock;
- The characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard.
- Synonyms: weakness; susceptibility; defencelessness.

2.4.3. Vulnerability Parameters and Indicators

The erosion phenomenon along the coastline as already mentioned, happens mostly due to natural processes and human activities. Among the most important factors contributing to it, stands out the limited transport of sediments to the coast from rivers and frequent flooding. The existence of coastal structures, changes resulting from human intervention in rivers and sand extraction are part of the group of agents that more deplete the natural nourishment to the coastline causing the so much-discussed coastal erosion.

Storm waves, *tsunamis* and sea level rise may cause permanent flooding that will have a considerable impact on the natural environmental and socio-economic conditions in the coastal zone. Over time, frequent coastal flooding may change the water quality, the characteristics of the aquifers, loss of life, loss of crops, and loss of tourist assets among others.

Several authors have proposed the assessment of coastal vulnerability, e.g. Gornitz *et al.* (1997) and Thieler and Hammar-Klose (1999). These authors compiled a set of vulnerability parameters and classified them, most of the cases in five classes. Then, they established according to the observed conditions on the study site, a qualitative degree of vulnerability usually ranked from 1 to 5.

In the following sub-chapters, a selection of the most common parameters used in the coastal vulnerability assessment process is made. They range from simple physiographic conditions of the coastal zones to more complex phenomenon, like local agitation, being necessary the collection of measured data measurement.

It is necessary to point of that some vulnerability parameters may present a given classification that will present effectively more vulnerability to erosion or more vulnerability to overtopping.

2.4.3.1. Topography

The topography is one of the leading and most noticeable features in the vulnerability assessment of coastal areas. Being a parameter whose setting is easy accessible, due to the simplicity of its content, it is added complexity when the desired level of detail is high. Sometimes the consideration of only this parameter may lead to antagonistic concerns when comparing different srudy zones.

Nicholls (1998) defines the practical topography term as the limit obtained by the maximum sea level in a return period of 100 years, added to the expected sea-level rise.

The proposal presented in Table 2.2 was based on the contribution made by Gornitz *et al.* (1997).

Table 2.2 - Vulnerability classification regarding topographic elevation (Coelho, 2005)

Topographic elevation referred to the hydrographic zero (m)	> 30	>20	> 10	> 5	≤ 5
		≤ 30	≤ 20	≤10	
Vulnerability	Very low	Low	Moderated	High	Very high
	1	2	3	4	5

Each rating will give important indications of the possible occurrence of floods, including its periodic character, and adopted the correspondence presented in Table 2.3.

Table 2.3 - Correspondence between the degree of vulnerability and the likely phenomenon (Coelho, 2005)

Vulnerability		Phenomenon
Very low	1	Very unlikely overtopping
Low	2	Overtopping
Moderated	3	Occasional overtopping
High	4	Likely flooding
Very High	5	Frequent flooding

Taking into account the information collected, topography is a very important aspect in a first approach to a coastal area.

2.4.3.2. Distance to the shoreline

The location of a particular asset facing the coastline, will determine the degree of vulnerability that presents. In fact, the closer a particular asset or infrastructure is the coastline, more vulnerable will be.

This parameter is not considered in most of the studies carried out, because the majority of these studies adopts a linear and simplistic approach in relation to the coastal area, assuming a single value of vulnerability index for the entire interior land that corresponds to a specific maritime front, disregarding any variation of topographic and geologic characteristics towards inland (Coelho, 2005).

Is a parameter with a subjective character as it does not reflect the right vulnerability of a given infrastructure or asset. A far away building located in a low sandy coast and without protection present a given level of vulnerability, however a close one and in a high rocky coast could not be vulnerable.

A vulnerability classification regarding the distance to the shoreline is then presented in Table 2.4. It is consider low vulnerability when distances of assets are higher than 1000 m.

Table 2.4 - Vulnerability classification regarding distance to the shoreline (Coelho, 2005)

Distance to the shoreline (m)	> 1000	> 200	> 50	> 20	≤ 20
		≤ 1000	≤ 200	≤ 50	
Vulnerability	Very low	Low	Moderated	High	Very high
	1	2	3	4	5

2.4.3.3. Geology

The geology classification is one of the relevant parameters when characterizing the coast. It is presented through geological maps, whose consultation makes the geological setting of a coastal stretch much more simplified. From these charts it is possible to evaluate the nature of rocks and sediments, enabling the creation of a rating based on the behaviour and scale of its hardness. Table 2.5 refers to a vulnerability classification of the geologic parameter.

Table 2.5 - Vulnerability classification regarding shore geology (Coelho, 2005)

Description	Vulnerability
Magmatic rocks (granite, gabbro and basalt)	1
Metamorphic rocks (schist, gneiss and marble)	2
Sedimentary rocks (limestone, sandstone and mudstone)	3
Unconsolidated large sediments	4
Unconsolidated small sediments	5

2.4.3.4. Geomorphology

The geomorphology, particularly of the coastal zone is understood as the branch of geology that studies the shape of the coastal surface.

Geomorphology's assessment is done in an expeditious way, through basic tools such as the human vision or Google Earth tool. This is not a difficult task and doesn't require such advanced knowledge of sciences, namely coastal engineering.

Coelho (2005) suggests a classification (Table 2.6) based on the proposal of Gornitz *et al.* (1997) about this item as a function of the observed morphological characteristics.

Table 2.6 - Vulnerability classification regarding geomorphology (Coelho, 2005)

Description	Vulnerability
Mountains	1
Rocky cliffs	2
Erodible cliffs, sheltered beaches	3
Exposed beaches, plains	4
Dunes, sandbanks and estuaries	5

2.4.3.5. Soil Covering

The vulnerability parameter related to soil covering, does not present a significant importance in relation to other types of parameters, however, highlights the different coastline behaviours depending on the type of soil covering.

The increased coastal waterproofing areas reduce the power of water nourishment from the surface by changing its interface with the seawater level and increasing and concentrating runoff. For example, this action may lead to erosion of the cliffs, to frequent flooding episodes among others.

The degree of vulnerability of a given soil increases according with its degree of change. Natural soil is less vulnerable as the vegetation creates, through their roots, stability and cohesion of the surrounding ground (Coelho, 2005).

Coelho (2005) presents a proposal for a soil covering classification parameter based on what was mentioned above, Table 2.7.

Table 2.7 - Vulnerability classification regarding soil covering (Coelho, 2005)

Description	Vulnerability
Forest	1
Underbrush's, cultivated soil, and gardens	2
Uncoated soil	3
Urbanized rural	4
Urbanized and industrial	5

It is considered that this is a factor with less weight on coastal vulnerability, than other parameters referred to. For this reason, it is important to consider these factors carefully and to establish proper weight factors (Coelho, 2005).

2.4.3.6. Tidal Range

The tidal range varies according to the place of study.

The classification presented in Table 2.8, Gornitz *et al.* (1997) presents a vulnerability classification of this parameter, function of tidal range registered on the coast.

Table 2.8 - Vulnerability classification regarding tidal range (Gornitz *et al.*, 1997)

Tidal range (m)	< 1.0	≥ 1.0 <2.0	≥2.0 ≤ 4.0	>4.0 ≤ 6.0	> 6.0
Vulnerability	Very low	Low	Moderated	High	Very high
	1	2	3	4	5

2.4.3.7. Significant Wave Height

The significant wave height, commonly referred as H_s, is a concept that reflects the average of the highest third of cumulative distribution of wave heights. The scheme of incident waves in a certain coastal zone is one of the main indicators of the potential sediment transport. In fact, there is a relationship between the wave height and the verified sediment transport (Coelho, 2005).

The classification of this parameter is highly variable in time and space and may differ considerably for the same area of study, in accordance with the sensitivity of the author. Gornitz *et al.* (1997) proposed a classification of this vulnerability parameter, likely to be applied on the Portuguese coast, Table 2.9.

Table 2.9 - Vulnerability classification of significant wave height (Gornitz *et al.*, 1997)

Maximum significant wave height (m)	< 3.0	≥ 3.0 < 5.0	≥ 5.0 ≤ 6.0	≥ 6.0 < 6.9	≥ 6.9
Vulnerability	Very low	Low	Moderated	High	Very high
	1	2	3	4	5

2.4.3.8. Accretion and Erosion Rates

The rate of coastal sediment transport is one of the measures most used by scientists and engineers, appearing in planning instruments to predict the future (Dolan *et al.*, 1991).

Accretion/erosion rate represents indicative values of sedimentary dynamics over time. It has as its main objective to quantify a "balance" that aims the knowledge of the coastline evolution resulting from the phenomena that occurred there.

The accuracy of this parameter depends on the accuracy of measurements of the coastline, the temporal variation, the number of points with measurements used on the rate calculation, the temporal proximity between the measurements, the temporal variation of trends, the date of the start of data acquisition and the method used in the calculation of the rate.

The past trends in the evolution of the coastline, the accretion/erosion rates registered in the past, related with possible interventions, are a valuable aid to the attempts of projection of future behaviour.

It is essential to check whether there is any significant variation of these rates, as a result of some intervention performed (Coelho, 2005).

Following, a vulnerability classification related to the accretion/erosion rates proposed for the Portuguese coast (Coelho, 2005).

Table 2.10 - Vulnerability classification regarding accretion/erosion rate (Coelho, 2005)

Accretion/erosion rate (m/year)	> 0	≥ -1	> -3	≥ 6.0	≤ - 5
	accretion	≤ 0	≤ -1	< -3	erosion
Vulnerability	Very low	Low	Moderated	High	Very high
	1	2	3	4	5

2.4.3.9. Anthropogenic Actions

The importance of studying the consequences of human interventions in the configuration of the coastal zone, has gained more and more attention in the research done in this field of knowledge. It is then, that the engineering interventions should be put together, with others whose potential for mitigation of negative effects are also promising, in order to understand the whole situation of vulnerability.

The human interventions with impacts in the rates of sediment transport in the coastline, such as hydroelectric plants, dredging works, breakwaters and groins, dredging works, urbanization in dynamic areas and the destruction of dune systems, increase the values of coastal erosion, increasing also the level of vulnerability. It is necessary to mitigate these consequences (Veloso-Gomes and Taveira-Pinto, 1997).

The classification of this type of vulnerabilities should be a function of the probability of the potential sediment transport (function of sea waves characteristics) be higher than the volume of sediment available, effect of sediment sources reduction (due to dredging works, hydroelectric power plants, breakwaters and groins). The likelihood of erosion due to human interventions with influence in the behaviour of natural coastal dynamics must include both negative effects of the interventions, but also the defence action of these interventions.

A classification regarding anthropogenic actions is presented in Table 2.11 which considers five degrees of intervention in the area of study (Coelho, 2005).

Table 2.11 - Vulnerability classification regarding anthropogenic actions (Coelho, 2005)

Description	Vulnerability
Interventions with shoreline maintenance position structures	1
Interventions with structures, with evidence of sedimentary sources reduction	2
Interventions without structures, but evidence of sedimentary sources reduction	3
Without interventions and without evidence of sedimentary sources reduction	4
Without interventions and evidence of sedimentary sources reduction	5

2.4.4. REPRESENTATION OF VULNERABILITY CHARTS

A vulnerability chart is a map representation that provides qualitative and quantitative information regarding the local conditions of sensitivity that the coastline faces from the environment. Usually it provides the representation in chart form of the classification of the previous vulnerability parameters or indicators, measured and considered for that coastal zone.

Some examples of vulnerability charts regarding some parameters previously referred(soil covering, geomorphology and accretion/erosion rate) are shown in the Figure 2.12.

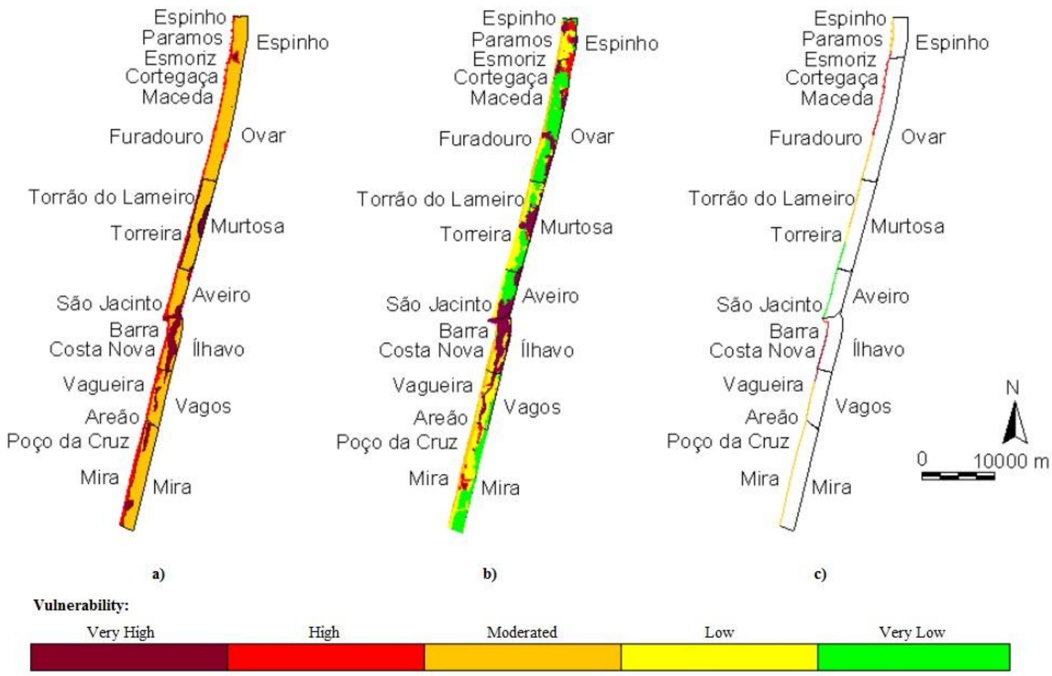


Figure 2.9 - Vulnerability charts regarding a) Geomorphology, b) Soil Covering and c) Accretion/Erosion Rate (Pereira and Coelho, 2013).

2.5. RISK IN COASTAL AREAS

The largely applied definition of risk has been defined as the product of the **probability of occurrence** of a given event by **the severity associated** to this event. It is a qualitative parameter however as presented, may have a quantitative classification, i.e., be defined in a specific scale:

$$\boldsymbol{Risk} = Probability\ of\ Occurence * Severity\ Associated$$

The concept of risk has been linked to many other concepts, nature of probability: probability, chance and danger. Scientifically technical measure of uncertainty or the characterization of the level of uncertainty with regard to each potential event identified is carried out by the concept of probability.

The risk magnitude is variable in time, either by changing the probability of occurrence of the actions that generate risk, either by the variation of the vulnerabilities of the coastal zone, either by a change of the consequences (Almeida, 2003).

The risks of exposure of urban areas to the energetic actions of the sea depend not only on the vulnerabilities of the coastline where they are located or if they deploy, but also of the characteristics of built waterfronts and urban settlements (extension, levels, proximity to water, volumetry, activities, etc.) (Coelho, 2005).

It is possible to identify coastlines with a high level of vulnerability to the energetic actions of the sea, but without great risk of exposure due to the lack of human occupation because this occupation is at a long distance, or the location has compatible uses with the occurrence of hydro-morphological changes expected in a long enough time horizon (Coelho, 2005).

This horizon will be different depending on whether it is a support for removable beach, a campsite, a settlement with great volumetry buildings or a complex of dangerous chemicals (Veloso-Gomes and Taveira-Pinto, 1997).

A correct classification of vulnerabilities and risks for the purposes of zoning and land-use planning should be done with consideration of numerous factors. The evaluation of processes and surrounding phenomena (to the extent that involves the studies in this area) is of high complexity and uncertainty associated with forecasting capacities (Coelho, 2005).

2.5.1. Risk Assessment

Some EU guidelines for risk assessment define it as group of three main stages,

1. risk identification;
2. risk analysis;
3. risk evaluation.

Three preliminary steps should be made before starting the three stages:

i. selection of the same target area;
ii. selecting the same time window;
iii. defining the same metric for the risk;

The risk assessment in the coastal zone has taken a growing importance in today's society. Its concept applies to events with negative effects that may happen in the future and is concerned that this probability of occurrence can be quantified or assessed, in order to overcome problematic situations and the ranking decisions (Coelho, 2005).

2.5.2. Risk Analysis

According to the ISO 31000 the risk analysis is one of the three stages of risk assessment process, and it is responsible for comprehending the nature of risk and determine the level of risk. It carries out a detailed estimation (as much quantitative as possible) of the probability of occurrence of an event or hazard and the severity of the potential impacts.

It is on the stage of risk analysis that should be established the geographic scope of the risk scenario and the of the impacts.

Risk Analysis should:

- allow maps representation with equal risk curves;
- allow the creation of risk classes as a function of the values obtained, and therefore the classification of different areas, serving as a tool to assist in the planning of the coastline and in decision-making for future interventions;
- be realized with calibration factors for assignment of respective risks.

The fact that the society is now a major player in the decision-making processes, the visibility of the situations, the increased consequences and responsibilities of damages, obliges engineers and stakeholders to improve safety levels and to reduce the levels of vulnerability. The risk of coastal erosion represents the undesired consequence of this phenomenon. There is a need for a review of effects magnitude and the importance of different impacts in the short and the long term in decision-making for future interventions (Coelho, 2005).

2.5.3 Human Impacts

Human impacts are the ones that should be reduced at any cost. Loss of life is the most important threat that coastal zones face. Risk assessment and its answers compose an important way to avoid or at least, reduce the life injuries.

None of the other types of risk should overlap the likelihood of loss of human lives. Several authors (Coelho, 2005) suggest that the quantification should be a function of the density of residential areas in study, which makes sense because the greater the number of inhabitants in the coastal zone the greater severity will cause if any extreme phenomenon happen.

Seasonal areas are areas where the risk of loss of human lives varies throughout the year. The human presence only for 'moments' make the risk vary, however does not cease to exist.

Andrade and Freitas (2002) proposed a classification of human impact due to storm waves, and other extreme events, based on population density, higher and lower than 10 inha./km^2. This classification was ranked only in two classes, 1 and 2, respectively lower than 10 inha./km^2 and higher than 10 inha./km^2. The risk classification of human impacts, Table 2.12, was the one proposed by Coelho (2005) and was ranked in five classes.

Table 2.12 - Risk classification of human impacts (Coelho, 2005)

Description	Risk Class
Unpopulated	Very low
Population density under 10 inha./km^2	Low
Population density between 10 and 50 inha./km^2	Moderated
Population density between 50 and 100 inha./km^2	High
Population density higher than 100 inha./km^2	Very high

2.5.4. Economic Impacts

Many coastal areas have tourism as main economic source, being considered vital to its maintenance. The value of the territory is a function of land use, therefore tourism areas have a lower risk than a front built with important infra-structures.

In the presence of real estate at risk, its assessment is of utmost importance. It is necessary to carry out a study to ascertain the presence of built territory. It must be understood that the vulnerability of a home for the elderly be affected by an extreme event is well above a campsite, which result in a risk as well.

An assessment of risk in economic terms based on housing density and economic activity is presented in Table 2.13. However it does not reflect directly the number of jobs involved, leaving open questions of expansion that currently exist in areas unexplored.

Table 2.13 - Risk classification of economic impacts (Coelho, 2005)

Description	Risk Class
Not edified and without economic activities	Very low
Low construction density and low economic activity	Low
Average construction density and low economic activity	Moderated
High construction density and economic activity	High
High construction density and high economic activity	Very high

2.5.5. Environmental Impacts

Environmental impacts refer to the consequences that animal and vegetal species may suffer during or after storm events. The permanent reconfiguration of the coast, consequence of storms and erosion events is a problematic situation for ecosystems.

However, and without having the importance of previously referred impacts, the environmental impacts should also be reduced in order to preserve the ecological value. A proposal of classification regarding these impacts is given on Table 2.14.

Table 2.14 - Risk classification of environmental impacts (Coelho, 2005)

Description	Risk Class
No threatened ecosystems	Very low
No threatened animal or vegetal species	Low
Some threatened species	Moderated
Threatened species of local fauna and flora	High
Important threatened ecosystems	Very high

The estimation of environmental risks should be more accurate because it can be a decisive factor for the local biodiversity. Nowadays, ecology of the environment should be maintained through many types of approaches, having a growing interest in protecting the coastal areas.

2.5.6. Heritage Impacts

The property hazards arise when, in the presence of buildings of historical and cultural value, its integrity is vulnerable and can be affected. It is necessary to protect against it. Examples of built heritage are precious items of local history and culture. The most common examples include: religious sites, forts and military fortifications, lighthouses.

Assessment of heritage impacts should have in mind the historic and cultural value of the study area, Table 2.15.

Table 2.15 - Risk classification of heritage impacts (Coelho, 2005)

Description	Risk Class
No built heritage	Very low
Some not classified buildings	Low
Typical buildings	Moderated
Some historical buildings	High
Historical classified buildings	Very high

2.6. Final Remarks

One of the main characteristics of the coastal zones that make them unique is the precious surrounding environment, favourable to the development of several activities. This environment attracts people and constitutes large urban centres along the coastline.

Especially during winters, sea waves, tides, currents and storms with high erosion potential hit the shore and alert the different actors responsible for the management and protection of the coastline.

By the reference of this problem, a good level of scientific knowledge is necessary, to form a basis to planning options and adaptation strategies. This knowledge comes as output from the risk assessment, overall process that needs to identify and quantify vulnerabilities.

The concept of vulnerability is defined as the circumstances of a community that makes it susceptible to the damaging effects of a hazard. It is possible to identify different types of vulnerabilities that coastal zones face and they can be described and quantified in parameters or indicators.

Risk concept is diversified and has many approaches, however as considered in this chapter, it is the product of the probability of occurrence of a certain event by its consequences. It rises due to the presence of people, assets, infrastructures but also ecological values. The various risk impacts should be identified and quantified in order to establish priorities on the planning and management of the coastline.

3
VULNERABILITY AND RISK ASSESSMENT METHODOLOGIES

3.1. INTRODUCTION

For a better planning and management of coastal zones, several methodologies and tools of vulnerabilities and risks analysis were developed. They can be classified as:

- Generic Methodologies, as a guideline for more specific vulnerability analysis;
- Computer-Based Models, that try to simulate all the sea and shoreline behaviours for a better understanding of coastal phenomena;
- Tools for vulnerability analysis;
- GIS-based Decision Support Systems.

The data from of coastal characteristics can be quiet diverse, like topography, bathymetry, geomorphology, geology, sea actions, like waves, tides and storms, etc. Also the knowledge of the possible consequences will define the precision level of the methodology.

The number of characteristics and parameters will determine how advanced is the methodology applied. It is a "linear" relation, the more they will be related, the more advanced will be the methodology.

3.2. SIMPLE APPROACHES TO COASTAL VULNERABILITY ANALYSIS

3.2.1. INTRODUCTION

This first section of this great group of methodologies is addressed to the first methodologies that were developed to assess coastal vulnerability. They were mainly qualitative and based on expert judgement. In the following sub-sections, some of them will be presented.

3.2.2.IPCC COMMON METHODOLOGY (CM)

One of the most important methodologies that deal with the vulnerability of coastal systems is the Common Methodology, IPCC - Inter-Governmental Panel on Climate Change (1991). This methodology is useful for coastal studies at the sub-national up to national and the global scale and has been tested is several trials around the globe. As appropriate use, this approach is most useful as an

initial, baseline analysis for country level studies where little is known about coastal vulnerability.

Preliminary assessments of probable impacts of accelerated sea-level rise were undertaken at national level for The Netherlands and the United States.

Vastly used on the coastal vulnerability assessment, it is characterized for its **data analysis and interpretation, both physical and socioeconomic parameters**, to help taking the decision on global impacts estimation **as like the seal-level rise**, **taking attention to territory losses**.

The Common Methodology had one of its first applications, in the preliminary assessments of probable impacts of accelerated sea-level rise, at national level for the Netherlands and the US. The tool approach has underpinned several subsequent vulnerability assessment procedures, including the studies by Harvey *et al.* (1999) and Wetland Risk Assessment procedure of van Dam *et al.* (1999).

Even modest increases is sea-level will result in a series of direct or primary impacts on coasts, such as erosion, inundation and low-lying areas, flooding and storm damage and salinization of groundwater and waterways. These are also likely to result in secondary impacts on infrastructures, livelihoods and health (Abuodha and Woodroffe, 2006).

According to the information presented at the IPCC website, it has as inputs and outputs:

- Key inputs - Physical and socioeconomic characteristics of the study area;
- Key outputs - Vulnerability profile and the list of future policy needs to adapt both physically and economically. A range of impacts of sea-level rise, including land loss and associated value and uses, wetland loss, etc.

It specifies, at the beginning, key scenario variables: global climate change including sea-level rise; socio-economic development; and response actions. In its original form it involves 7 steps, and 8 in the developments made in the study made by Harvey *et al.* (1999) (Table 3.1, adapted from Abuodha and Woodroffe (2006).

Those steps are listed below:

1. Delimitation of the study area;
2. Inventory of the study area's characteristics;
3. Identification of the relevant socioeconomic development factors;
4. Assessment of physical changes;
5. Formulation of response strategies;
6. Assessment of the vulnerability profile;
7. Identification of future needs.

Table 3.1 - Comparison of the IPCC Common Methodology for vulnerability assessment procedures and its refinement in an Australian context (adapted from (Abuodha and Woodroffe, 2006)

	IPCC CM	Harvey *et al.* (1999)
Definition of the study area	Step 1	Steps 1 and 2
Data collection	Steps 2 and 3	Steps 3 to 6
Assessment	Steps 4 and 6	Steps 7
Responses	Steps 5 and 7	Step 8

The CM application in the Australian context was found deficient because the biophysical framework is not adequate to support the engineering and cost-benefit stages (Abuodha and Woodroffe, 2006).

Furthermore on its application, CM uses monetary valuations as an estimate of a coastal nation's vulnerability to future sea-level rise, employing a cost-benefit test to assess the preferred response option to mitigate future coastal impacts. Beyond this, it is composed by a list of analysis that should be done, however it is given the choice for the user how it should be made. The information available for the result of the application of the methodology is usually used as the basis for further physical and economic modelling.

Table 3.2 presents a reference about some important directions while applying IPCC Common Methodology.

Table 3.2 - Validity, ease of use and computer requirements of the IPCC Common Methodology (UNFCC, 2016)

Validity	Used in many coastal countries. Examples of studies: (Harvey *et al.*, 1999, Kay *et al.*, 1996, Kay *et al.*, 1992, McLean and Mimura, 1993, Waterman, 1996, Woodroffe and McLean, 1993)
Ease of Use	Requires considerable knowledge on a range of techniques for estimating biophysical and socioeconomic impacts of sea-level rise and adaptation.
Computer Requirements	Methodology does not explicit state how to perform analyses; analytical method chosen by user will determine the computer needs.

Applied across 46 case studies in 25 countries by the time of the World Coasts Conference in 1993 (IPCC, 1994) a number of concerns have been raised with this approach (McLean and Mimura, 1993) largely due to the fact that the biophysical framework is not adequate to support engineering and cost-benefit stages of vulnerability and adaption assessment e.g. (Kay and Waterman (1993), Kay *et al.* (1996), Woodroffe and McLean (1992), Woodroffe and McLean (1993)). Of particular concern was the poor application of this methodology for subsistence economies and the fact that the conception of the coastal zone was relatively narrow (Klein and Nicholls, 1999).

3.2.2. UNEP Methodology

The United Nations Environment Program developed a Handbook on Methods for Impact Assessment and Adaptation Strategies, designed to assist developing countries to conduct climate change impact and adaptation assessments, as inputs to the National Communications as required by the United Nations Framework Convention on Climate Change (UNFCCC) (Carter *et al.*, 1996).

Chapter 7 of this Handbook on Methods for Impact Assessment and Adaptation Strategies is dedicated to the assessment of coastal vulnerability. It provides an elaboration of the IPCC Technical Guidelines for the specific situation of assessing the impacts of sea-level rise on coastal zones, and it is based on a combination of widespread experience using the Common Methodology and other methods for coastal vulnerability assessment, which have been developed in response or addition to the Common Methodology e.g. (Gornitz *et al.*, 1994, Kay and Hay, 1993, Leatherman and Yohe, 1996, Nicholls *et al.*, 1995, Yamada *et al.*, 1995)).

UNEP supports the development of global, regional and national harmonized environmental data and databases, especially geo-referenced indicators for environmental assessments and early warning systems and procedures. The UNEP methodology establishes a generic framework for analysing and responding to problems of sea-level rise and climate change.

This generic approach to coastal vulnerability is not intended to be descriptive as to the use of scenarios or methods to be applied for the impacts and adaptation options. Instead, it encourages users to select those scenarios and methods that are most appropriate to their specific situation.

It consists of seven steps:

i. Define the problem;
ii. Select the method of analysis;
iii. Test the method;
iv. Select scenarios;
v. Assess the biogeophysical and socioeconomic impacts
vi. Assess the autonomous/natural adjustments and
vii. Evaluate adaptation strategies.

The last step is itself split into seven sub-steps. At each step, methods for the assessment of biogeophysical and socio-economic impactsare suggested but the choice is left to the user. This approach is useful in a range of situations, including sub-national or national level studies.

The UNEP approach might constitute an initial study, or follow earlier studies such as those completed using the IPCC Common Methodology, or be a quick screening assessment prior to more detailed vulnerability assessment (Klein and Nicholls, 1999).

Information gathered with this methodology can then be used as input for future modeling. Qualitative or quantitative physical and socioeconomic characteristics of the national coastal zone are the key inputs resulting in evaluation of a range of user-selected impacts of sea-level rise and potential adaptation strategies according to both socioeconomic and physical characteristics.

3.3. Techniques and Methods for Vulnerability and Risk Assessment

3.3.1. Introduction

In this section some techniques and methods used to describe and assess vulnerability and risk on the coastal zone will be presented.

3.3.2. Aerial Videotape-Assisted Vulnerability Analysis (AVVA)

The Aerial Videotape-Assisted Vulnerability Analysis (AVVA) is a method considered fast and low cost, to meet the frequent lack of data in coastal areas studies (Coelho, 2005). It is a semi-quantitative and qualitative method, so the experience and analysis capabilities of the users are a key factor. These difficulties may be overcome, if the first-order data set is validated or improved using topographic and geological maps and information on site. The method is easily adaptable to collect useful data on related subjects, such as vulnerability to storms, erosion and flooding (Andrade and Freitas, 2002).

As its name indicates, the method consists in analysing the vulnerabilities based on aerial observation of coastal regions and requires the following steps:

- Oblique aerial video recording of the coast to capture aspects of geomorphology, land use, types of occupation, defences and building density along the coast among others;
- Archival research (maps, aerial photographs, technical reports, scientific literature);
- Ground truth (verification of particular coastal characteristics);
- Data analysis and processing.

Some authors have applied this technique and obtained good results. organized the data collected by AVVA technique, classifying them into natural attributes and socio-economic partner attributes.

Table 3.3 presents the classification system based on natural attributes used in the approach of Andrade and Freitas (2002).

Table 3.3 - Natural attributes regarding geomorphology (Andrade and Freitas, 2002)

Natural Attributes	Coastal geomorphology	Beaches
		Wetlands
		Cliffs (no beaches)
		Hardened (protected)
	Inland geomorphology	Flatland
		Hilly land
		Mountainous
		Wetlands
	Evolution Trend	Stable/Accretion or stabilized by protection works
		Tendency to erode
		Erosion

The classification system based on natural attributes refers to the coastal geomorphology, inland geomorphology and the evolution trend.

Table 3.4 lists the classification of socioeconomic attributes considered relevant to evaluation of risk which adds population density and coastal development to the original system (Andrade and Freitas, 2002).

Table 3.4 – Socio-Economic classification system (Andrade and Freitas, 2002)

Protection (if present)	Seawall
	Bulkhead
	Groin
	Jetty
	Protected harbour
Land Use	Urban/City
	Residential
	Industry
	Tourism
	Agriculture
	Forest
	Barren
	Shrub/Grass/Herbs
Population Density	High (>10 inha/km^2)
	Low (<10 inha/km^2)
Coastal Development	High
	Loss

Socio-economic attributes refer to the protection and defence structures, land use in the coastal front, population density and level of coastal development.

AVVA will not be further described because of the minor importance relatively to the scope of this work; however this technique shows to be an important first approach to the coastal zones risk assessment.

3.3.3. Simple Multi Attribute Ratting Technique (SMART)

In Portugal, the work done in risk assessment started some decades ago, in 1980 and 1990. One of the first successful approaches to obtain risk derived from all the coastal issues was made by Andrade and Freitas (2002). However the application is not fully of the interest of this study, a resumed was made in order to understand a little bit more in the case of Portugal.

SMART is a convenient way to access the calculation of risk. It has many applications in lots of fields, and some researchers have tried to apply it in their studies. SMART approach is described in full in Goodmin and Wright (1991) and was adapted to assess impacts of forcing upon the Portuguese coast and to rank sections of these coast in terms of vulnerabilities and risks in relation to sea-level rise and storms (Andrade and Freitas, 2002). These authors proved to be applicable to various situations of vulnerabilities and risk classifications associated with coastal problems (Coelho, 2005).

It consists in dividing the study area in the same small cell dimension, analysing each one separately, instead of attempting a holistic view on early stages of the study. Lists of attributes should be established relevant to the problems under study.

Thus, each cell is likely to be characterized by a number of qualitative or quantitative (discrete or continuous) attributes that, regardless its nature must be assigned values within each cell. During this phase of the process a careful analysis should be carried out to avoid redundancies.

The elimination of extreme unbalance values or classification of each attribute is the next step in the process and can be carried out by a statistical analysis of standardization with the nearest normal distribution curves (Andrade and Freitas, 2002).

The basic data set obtained by the AVVA technique has been reorganized in four attributes, which are relevant to assess coastal vulnerability using the SMART approach, Table 3.5:

- Coastal contents (first order features) - which describe the seaward predominant content of a cell, with relevance to geomorphology;
- Coastal contents (second order features) - which describe the predominant content standing immediately landward of the 1st order feature;
- Protection;
- Evolution trend.

Table 3.5 lists these attributes used to describe coastal vulnerability to land loss and ranking of the performance of each attribute in relation to land loss. The ranking index grows with increasing vulnerability of the coast.

Table 3.5 - Attributes used to describe vulnerability of the coast to land loss (Andrade and Freitas, 2002)

<table>
<tr><th colspan="2">Attribute</th><th>1st order features</th><th></th><th>Rank</th><th>2nd order features</th><th>Rank</th></tr>
<tr><td rowspan="9">Coastal contents</td><td rowspan="7">Natural</td><td rowspan="3">Sandy Coast</td><td>Barriers</td><td>5</td><td>Low dunes</td><td>6</td></tr>
<tr><td>Pocket beach</td><td>4</td><td>High dunes</td><td>5</td></tr>
<tr><td>Open beach</td><td>4</td><td></td><td>2</td></tr>
<tr><td rowspan="2">Cliffed coast</td><td>Rocky (hard)</td><td>2</td><td>Cliff (rocky)</td><td>2</td></tr>
<tr><td>Erodible (soft)</td><td>3</td><td>Cliff (erodible)</td><td>3</td></tr>
<tr><td></td><td></td><td></td><td>Coastal plain, flatland</td><td>4</td></tr>
<tr><td>Wetland</td><td></td><td>5</td><td>Wetland</td><td>6</td></tr>
<tr><td rowspan="2">Artificial</td><td rowspan="2">Hardened, protected</td><td rowspan="2"></td><td rowspan="2">1</td><td>Hardened, protected</td><td>1</td></tr>
<tr><td>Hilly, mountainous</td><td>1</td></tr>
<tr><td rowspan="4">Protection works</td><td>No protection</td><td rowspan="4"></td><td></td><td></td><td></td><td>4</td></tr>
<tr><td>Jetty, Groin</td><td></td><td></td><td></td><td>3</td></tr>
<tr><td>Seawall, Bulkhead</td><td></td><td></td><td></td><td>2</td></tr>
<tr><td>Protected Harbour</td><td></td><td></td><td></td><td>1</td></tr>
<tr><td rowspan="3">Evolution Trend</td><td>Erosion confirmed</td><td rowspan="3"></td><td></td><td></td><td></td><td>3</td></tr>
<tr><td>Erosion trend</td><td></td><td></td><td></td><td>2</td></tr>
<tr><td>Accretion, stable</td><td></td><td></td><td></td><td>1</td></tr>
</table>

One approach to the evaluation of longshore distribution of risk to land loss has been undertaken using a SMART-borne index resulting from the additive aggregation of vulnerability with a proxy of coastal value. The aggregation of the results of each cell, by addition or multiplication, allows the combination of a plurality of attributes and thus a first order approximation to the classification of vulnerabilities and risks.

Table 3.6 lists attributes used to describe the occupation value of the coast in terms of socio-economic features and rank index of each attribute's performance in relation to land-loss.

Table 3.6 - Socio-economic attribute and rank used in SMART approach (Andrade and Freitas, 2002)

<table>
<tr><th>Attribute</th><th></th><th>Rank</th></tr>
<tr><td rowspan="2">Population density</td><td>High (> 10 inha/km^2)</td><td>2</td></tr>
<tr><td>Low (< 10 inha/km^2)</td><td>1</td></tr>
<tr><td rowspan="2">Coastal development</td><td>High</td><td>2</td></tr>
<tr><td>Low</td><td>1</td></tr>
</table>

Risk has been ranked in five classes (very low to very high) using the criteria and boundaries described in Table 3.7. The information on risk yielded by this method is specific of the area under analyses (in this case the Portuguese mainland coast).

Table 3.7 - Classification of Risk (Andrade and Freitas, 2002)

Class	Standard intervals	Standard values	Rank
Very low	$x_i \leq x_{average} - 1.6\sigma$	]- ∞; 4.05]	1
Low	$x_{average} - 1.6\ \sigma \geq x_i$ $x_{average} - 0.5\ \sigma \geq x_i$	]- 4.05; - 1.28]	2
Medium	$x_{average} - 0.5\ \sigma < x_i$ $x_{average} + 0.5\ \sigma \geq x_i$	]- 1.28; 1.26]	3
High	$x_{average} + 0.5\ \sigma < x_i$ $x_{average} + 1.6\ \sigma \geq x_i$	]1.26; 4.04]	4
Very High	$x_i \geq x_{average} + 1.6\ \sigma$	] 4.04; ∞]	5

The very extreme risk ranking, either very high or very low, usually corresponds to well defined and repetitive features. Very low risk sections are associated with armoured ports, rocky headlands and resistant cliffs. The highest risk sections coincide with (1) highly land value in different geographic context; and (2) fast eroding cliffs, spits/barriers sheltering wetlands and beaches, in association with different occupation values of the hinterland (Andrade and Freitas, 2002).

The translation and representation of the results, through charts or maps would be easy to implement. The assessment of land at risk departing from Nicholls' method (Nicholls *et al.*, 1995) provides an independent and complementary picture (Figure 3.1), which yields absolute results and yet refers to only one dimension – the coastal length (Andrade and Freitas, 2002).

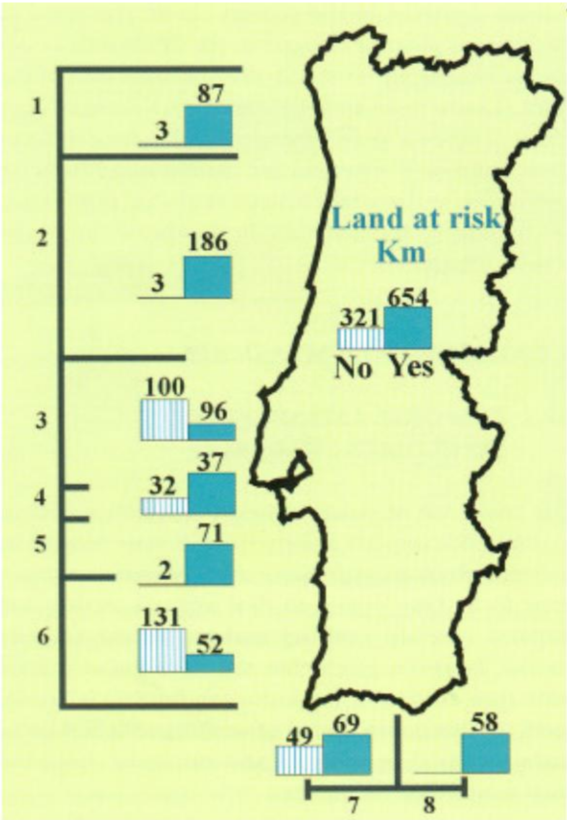


Figure 3.1 - Distribution of land at risk in different stretches of the Portuguese coast and summary data for all the country (Andrade and Freitas, 2002)

3.3.4. Coastal Zone Simulation Model (COSMO)

COSMO was created by the Coastal Zone Management Centre and Resource Analysis, The Netherlands and it is a decision support model to evaluate potential management strategies under different scenarios, including long-term climate change.

COSMO demonstrates the main steps in the preparation, analysis and evaluation of the Coastal Zone Management (CZM) plans. It helps in the formulation of alternative plans for development projects and for environmental and coastal protection measures.

The program is an interactive tool that allows coastal zone managers to explore the impacts of development projects and environmental protection measures. As a particular feature, COSMO facilitates the analysis of impacts of present-day actions on a region's long term vulnerability for a possible accelerated rise in sea level due to climate change.

The user can explore a number of predefined cases as an educational tool, or specify new development scenarios and combinations of measures as a decision-making tool. A more complex version of COSMO has been developed to demonstrate some more realistic characteristics, constraints and limitations of institutional arrangements for Coastal Zone Management.

The program simulates day-to-day management of a coastal zone from the perspective of four organizations:

- the city government;

- the public works department;
- the environment department;
- the private sector.

Each of these four entities takes annual decisions, within their means/budget and mandate, to further their own objectives.

Structure of COSMO

COSMO guides the user through five steps in the analysis of promising strategies under different scenarios, which represent assumptions on exogenous conditions, such as sea-level rise. These five steps are listed below:

- Analysis of the system characteristics and current future problems;
- Analysis of conditions, setting of objectives and criteria to meet;
- Formulation of coastal zone management strategies by selecting measures to be undertaken;
- Analysis of coastal zone management strategies and objectives reached;
- Evaluation of coastal management strategies by comparison and review.

This structure is based on the work of the IPCC, namely the Common Methodology that was used as a first step to its formulation.

COSMO Software

The Coastal Zone Simulation Model starts with an opening screen, Figure 3.2 that includes an introduction text where presents information such as the terminology used in COSMO. The lower five buttons represent each of the five steps of analysis.

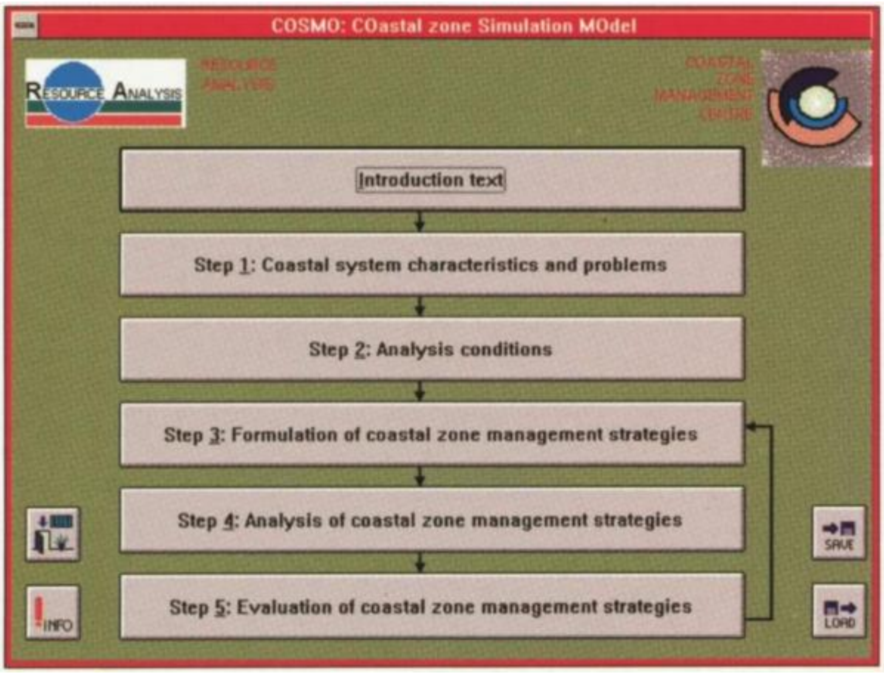


Figure 3.2 - Opening screen of COSMO tool (CZMC and Resource Analysis, 1994)

During each step of COSMO, different screen appear with new information and buttons. The 'INFO' button provides the user with some additional information about the actual screen.

The user can explore a number of predefined cases that are advised to study to complete the first round of COSMO. Then, the user should return to step 2 in order to modify the coastal zone management scenarios and to continue through step 3, creating strategies according to his own objectives.

These modified scenarios and strategies can then be analysed and evaluated in steps 4 and 5. The analysis of combination of scenarios allows the assessment of the sensitivity of a system to these external effects.

Instead of the promising features one of this first attempt to develop a decision support system, COSMO was not able to be applied to other study places, however it do have educational value.

3.4. INDEX-BASED METHODS

A large number of index-based methods have been developed as rapid and consistent methods for characterizing the relative vulnerability of different coasts. The simplest of these are assessments of the physical vulnerability of the coast, while the more complex also examine aspects of economic and social vulnerability (Abuodha and Woodroffe, 2006).

Index-based methods express coastal vulnerability by a one-dimensional, and generally unitless, risk/vulnerability index (Ramieri *et al.*, 2011). This index is calculated through the quantitative or semi-quantitative evaluation and combination of different parameters. Some examples of these parameters have been already presented in Chapter 2, as a phase of the process to assess vulnerability on coastal zones when quantitative data isn't available.

Largely applied all over the world, Coastal Vulnerability Indices (CVI), one type of index-based methods, form an easy basis of evaluation of the coastal vulnerability of physical, socio-economic and environmental.

This approach is not immediately obvious since the final index doesn't enable the understanding of assumptions and aggregations that led to its calculation. A clear explanation of the adopted methodology is essential to select the proper use of index-based approaches (Ramieri *et al.*, 2011).

As widely recognized (Ramieri *et al.*, 2011), the greatest limitation of this formulation is the incapacity to address socio-economic aspects (such for example the number of people affected, infrastructures potentially damaged and economic costs) in the assessment of coastal vulnerability (Cooper and McLaughlin, 1998, Gornitz *et al.*, 1994).

Gornitz and Kanciruk (1989) developed one of the first attempts to assess coastal vulnerability index to climate change, particularly sea-level rise considering inundation and flooding, and susceptibility to erosion. Gornitz (1991) suggested that this index could be applied in a global context, although its application was only demonstrated for the United States in that study. Later, it was recognized that this index could be improved if it had a term related to storm frequency, and if it included a term related to population at risk (Gornitz *et al.*, 1991).

Many other authors based on the work o Gornitz (1991) developed other CVI in places which was needed an evaluation to further utilization in issues related to policy and planning decision. Some of them are presented in Table 3.8 (Abuodha and Woodroffe, 2006).

Table 3.8 - Summary of coastal vulnerability indices, their geographical application and the variables needed to implement them (Abuodha e Woodroffe, 2006)

Index	Geographical Application	Variables considered	Reference
Coastal vulnerability index (CVI)	USA	Relief, vertical land movement, lithology, coastal landform, shoreline displacement, wave energy, tidal range	(Gornitz, 1991, Gornitz and Kanciruk, 1989, Gornitz *et al.*, 1991)
Coastal Vulnerability index (CVI)	USA	Historic shoreline erosion rates, geomorphology, relative rates of sea-level rise, coastal slope, wave height, tidal range	(Thieler *et al.*, 2000)
Social vulnerability index (SoVI)	USA	Principal components analysis of Census-derived social data	(Boruff *et al.*, 2005)
Coastal social vulnerability score (CSoVI)	USA	Combination of CVI and SoVI	(Boruff *et al.*, 2005)
Sensitivity index (SI)	Canada	Relief, sea-level trend, geology, coastal landform, shoreline displacement, wave energy, tidal range.	(Shaw *et al.*, 1998)
Erosion Hazard index	Canada	As SI, plus exposure, storm surge water level.	(Forbes *et al.*, 2003)
Risk Matrix	South Africa	Location, infrastructure (economic value), hazard.	(Hughes and Brundrit, 1992)
Sustainable capacity index (SCI)	South Pacific	Vulnerability and resilience of natural, cultural, institutional, infrastructural, economic and human factors.	(Yamada *et al.*, 1995)
Sensitivity index	Ireland	Shoreface slope, coastal features, coastal structures, access, land use.	(Carter, 1990)
Vulnerability index	UK	Disturbance event frequency, relaxation (recovery) time.	(Pethick and Crooks, 2000)

Following, some references about some studies done on several countries applying an index-based method addressing coastal vulnerability parameters.

USA

A coastal vulnerability index, as proposed by Gornitz, has also been incorporated into an analysis of many of the shorelines of the United States Geological Survey (USGS). This coastal vulnerability index is derived to show relative vulnerability; it combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, yielding a relative measure of the system's natural vulnerability to the effects of sea-level rise.

Several researchers have seen a need to incorporate data on storm and storm-surge occurrence and frequency, as also to incorporate social data on people at risk. In this context, the most detailed analysis is the social vulnerability one by (Boruff *et al.*, 2005). The social vulnerability index (SoVI) uses socio-economic variables on a coastal country basis in a principal components analysis (PCA) to produce the overall coastal social vulnerability score (CSoVI).

Canada

In Canada a sensitivity index (SI) has been developed for the entire Canadian coastline, where the index is scaled between 1 and 5 with a final ranking as low, moderate or high. A shortcoming at this scale is that numerous areas of high sensitivity are overlooked because of the scale and the method of scoring. Attributes concerning the Canadian coast are contained in a Coastal Information System (CIS), and this can be used to calculate the sensitivity index (SI) (Shaw *et al.*, 1998), or further variables can be added, as has been adopted locally to derive an erosion hazard index (EHI) (Forbes *et al.*, 2003).

South Africa

A further modification was undertaken by Hughes and Brundrit (1992) for application to the South African coast. In this case the index needed modifications because of the shortage of data on shore displacement (ongoing shoreline change) and vertical land movements. An element that assessed economic value in terms of infrastructure was developed, so that the index could address location and infrastructure at risk.

Pacific

In the Pacific, vulnerability has been assumed using an approach developed from the Common Methodology advocated by Kay and Hay (1993) that assess both vulnerability and resilience.

Vulnerability is scaled from -3 to 0, and resilience is scaled 0 - 3. This evaluation is undertaken across a series of sectors including (Kay and Hay, 1993):

- natural (biophysical);
- cultural (communal, national);
- institutional (village, national);
- infrastructural (individual, communal, national);
- economic (subsistence, cash); and
- human (populations).

These values are then summed into a Sustainable Capacity Index (SCI). An SCI is calculated for existing conditions and estimated under response strategies in order to assess the effectiveness of adaptation (Yamada *et al.*, 1995).

Portugal

In Portugal, Coelho (2005) in his proposal for a classification vulnerability index, as presented in the second chapter, focused on the following seven variables:

- Distance to the shoreline;
- Geology;
- Geomorphology;
- Land use;
- Tidal range;
- Rate of erosion and accretion; and
- Anthropogenic actions.

3.4.1. Coastal Vulnerability Index (CVI)

The CVI provides a simple numerical basis for ranking sections of coastline in terms of their potential for change that can be used by managers to identify regions where risks may be relatively high (Ramieri *et al.*, 2011).

The first methodological step deals with the identification of key variables representing significant driving processes influencing the coastal vulnerability and the coastal evolution in general (Gornitz *et al.*, 1991).

As successively described, the number and typology of key variables can be slightly modified according to specific needs, but in general CVI formulation includes 6 or 7 variables. The second step deals with the quantification of key variables.

Although various methodologies may be available for this step, quantification is generally based on the definition of semi-quantitative scores according to a 1-5 scale (Gornitz, 1990, Hammar-Klose and Thieler, 2001) where 1 indicates a low contribution to coastal vulnerability of a specific key variable for the studied area or sub-areas, while 5 indicates a high contribution.

At the third step, key variables are integrated in a single index. Gornitz *et al.* (1992) and Gornitz *et al.* (1997) proposed and tested (in terms of sensitivity analysis) different formulas (considering 7 key variables) for the derivation of the final CVI (Table 3.9).

Table 3.9 - Formulas tested Gornitz *et al.* (1992) and Gornitz *et al.* (1997) to derive the final CVI index (ETC CCA, 2011)

Product mean	$CVI_1 = \frac{(x_1 . x_2 . x_3 . x_4 \ldots . x_n)}{n}$
Modified product mean	$CVI_2 = \frac{[x_1 . x_2 . \frac{1}{2}(x_3 + x_4) . x_5 . \frac{1}{2}(x_6 + x_7)]}{n-2}$
Average sum of squares	$CVI_1 = \frac{({x_1}^2 . {x_2}^2 . {x_3}^2 . {x_4}^2 \ldots . {x_n}^2)}{n}$
Modified product mean	$CVI_4 = \frac{(x_1 . x_2 . x_3 . x_4 \ldots . x_n)}{5^{(n-4)}}$
Square root of product mean	$CVI_5 = (CVI_1)^{1/2}$
Sum of products	$CVI_6 = 4.x_1 + 4.x_2 + 2 * (x_3 + x_4) + 4.x_5 + 2.(x_6 + x_7)$

where

- x_1 is the mean elevation;
- x_2 is the local subsidence trend;
- x_3 is the geology;
- x_4 is the geomorphology;
- x_5 is the mean shoreline displacement;
- x_6 is the maximum wave height; and
- x_7 mean tidal range.

Finally, at the fourth step, the CVI values are then classified in n different groups (usually 3 or 4), using n-1 percentiles as limits. This classification enables the evaluation of the relative coastal vulnerability of the different studied coastal parcels.

The CVI formulation based on the square root of product mean (CVI_5) has been widely used in other applications at the local, regional and supra-regional level. The U.S. Geological Survey (USGS) used this formulation to evaluate the potential vulnerability of the U.S. coastline at the national scale (Thieler and Hammar-Klose, 1999).

In particular, this CVI considered six variables, combined through the following equation:

$$CVI = \sqrt[2]{\frac{a_1 . a_2 . a_3 . a_4 . a_5 . a_6}{6}}$$

where

- a_1 is the geomorphology;
- $a_2$is the shoreline change rates;
- a_3 it's the coastal slope;
- a_4 it's the relative sea level rate;
- a_5 it's the mean significant wave height, and

- a_6 it's the mean tidal range;

Another application of this CVI was the case of Andalusia coastline (around 800 km in length) (Ojeda *et al.*, 2009), which was calculated for coastal parcels of 200 m. Results of the analysis have been mapped through a GIS system, thus enabling the identification of the most vulnerable areas at fine spatial scales, Figure 3.3.

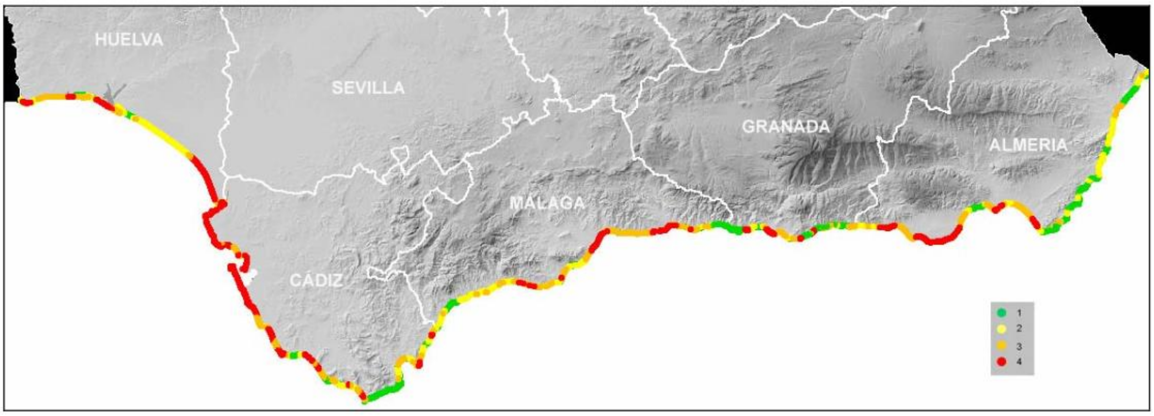


Figure 3.3 - Coastal Vulnerability Map for Andalusia (Ojeda *et al.*, 2009)

Other authors slightly adapted the CVI to a particular coastal zone or region, modifying not only the number but also the typology of key variables. Abuodha and Woodroffe (2006) for example applied the CVI to seven beaches of the Illawara Coast in Australia. The CVI was customized to this purpose; in particular the formulation considered different key variables (but again the CVI_5 formulation), i.e.:

$$CVI = \sqrt[2]{\frac{a_1 . a_2 . a_3 . a_4 . a_5 . a_6 . a_7}{7}}$$

where

- a_1 is the dune height;
- a_2 is the barrier type;
- a_3 is the beach type;
- a_4 is the relative sea-level change;
- a_5 is the shoreline erosion or accretion;
- a_6 is the mean tidal range;
- a_7 is the mean wave height.

The first three variables replace the "a_1" and "a_3" variables (geomorphology and coastal slope, respectively) identified by Thieler and Hammar-Klose (1999).

Table 3.8 and Figure 3.4 respectively illustrates the ranking scores of key variables considered for the Illawara coast and vulnerability maps for three example beaches (Bulli, Stanwell Park and Warilla).

Table 3.10 - Ranking scores of key variables for the Australian beach case Abuodha and Woodroffe (2006) (Ramieri *et al.*, 2011)

	Very Low	**Low**	**Moderate**	**High**	**Very high**
Variable	**1**	**2**	**3**	**4**	**5**
Dune height (m)	> 30.1	20.1 - 30.0	10.1 - 20.0	5.1 - 10.0	0 - 5.0
Barrier types	Transgressive	Prograded	Stationary	Receded	Mainland beach
Beach types	Dissipative (D) Longshore bar trough (LBT)	Rhythmic bar beach (RBB)	Transverse bar rip (TBR)	Low tide terrace (LTT)	Reflective (R)
Relative sea-level change (mm/yr)	≤ -1.1 Land rising	-1.0 - 0.99	1.0 - 2.0 Eustatic rise	2.1 - 4.0	≥ 4.1 Land sinking
Shoreline erosion accretion (m/yr)	≥ +2.1 Accretion	1.0 – 2.0 Stable	-1.0 - +1.0 Erosion	-1.1 - -2.0 Erosion	≤ -2.1 Erosion
Mean tidal range (m)	≤ 0.99 Microtidal	1.0 – 1.9 Microtidal	2.0 – 4.0 Mesotidal	4.1 – 6.0 Mesotidal	≥ 6.1 Macrotidal
Mean wave height (m)	0 – 2.9	3.0 – 4.9	5.0 – 5.9	6.0 – 6.9	≥ 7.0

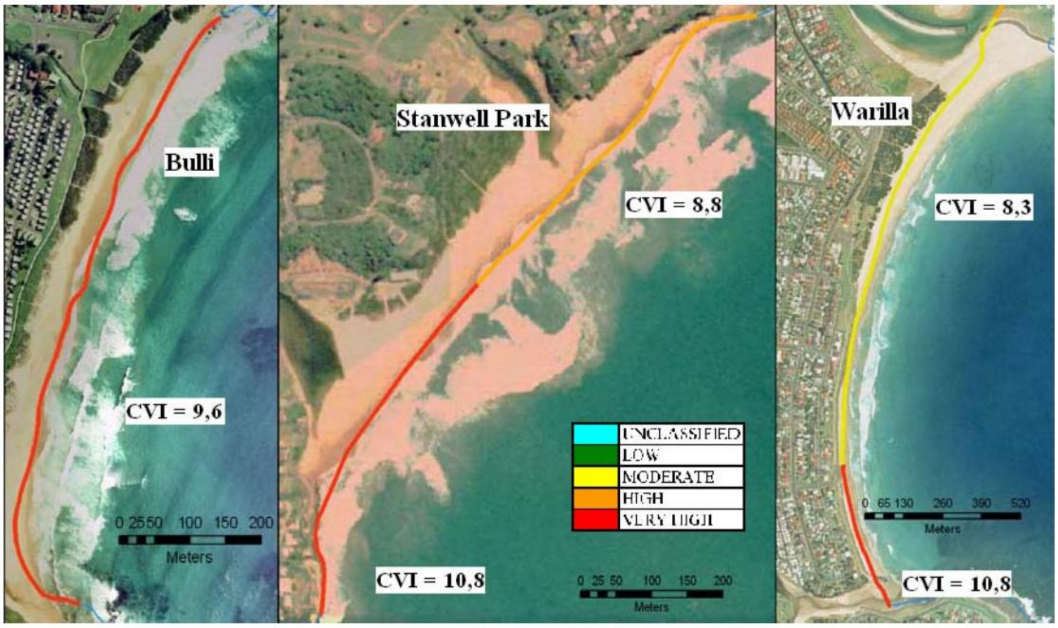


Figure 3.4 - Coastal Vulnerability Map for beaches of Illawarra coast in (Abuodha and Woodroffe, 2006)

3.4.2. Coastal Vulnerability Index for sea-level rise - CVI (SLR)

Özyurt (2007) and Ozyurt *et al.* (2008) developed a CVI to specifically assess impacts induced by sea level rise. The index is determined through the integration of 5 sub-indices, each one corresponding to a specific sea-level rise related impact. The author applied this methodology to the Göksu Delta in Turkey, where the five considered SLR impacts were:

- coastal erosion;

- flooding due to storm surges;
- permanent inundation;
- salt water intrusion to groundwater resources; and
- salt water intrusion to river/estuaries.

Each sub-index is determined by the semi-quantitative assessment of both physical and human influence parameters. In the case of the Göksu Delta analysis, 12 physical and 7 human influence parameters were considered. Each parameter may contribute to the definition of more than one sub-index.

A value ranging between 1 and 5 is assigned to each parameter, in relation to its severity and contribution to the vulnerability of the analysed coastal system.

Each sub-index (related to a specific SLR impact) is calculated by the following formula:

$$CVI_{impact} = \frac{(0.5 \times \sum_1^n PP_n) + (0.5 \times \sum_1^m HP_m}{CVI_{least\ \ vulnerable}}$$

where

- PP is the physical parameter;
- HP is the human influence parameters;
- n and m are the number of physical an human influence parameters, respectively, considered for a particular impact;
- $CVI_{\text{least vulnerable}}$ is the value of the sub-index for the least vulnerable theoretical case, meaning all parameters equal to 1.

CVI index values vary between1 and 5, and are integrated in an overall final index CVI (SLR), according to the following formula:

$$CVI\ (SLR) = \frac{\sum_{i=1}^{5} Total\ Impact_i}{\sum_{i=1}^{5} Least\ Vulnerable\ Case_i}$$

The above formula integrates all the five sub-indexes. However the CVI (SLR) index may be also determined by integrating only a subset of the five considered impacts, those playing a more relevant role in the vulnerability of the studied coastal system.

Özyurt (2007) stresses the importance to include at least the following impacts in the definition of the final index: coastal erosion, flooding and permanent inundation. Results of the analysis can be described through a matrix, such as the one developed for the Göksu Delta, also illustrating the contribution of each specific parameter and sub-index to the overall coastal vulnerability.

3.5. Methods based on Dynamic Computer Models

3.5.1 Introduction

Methods based on dynamic computer models allow to integrate the time dimension in the analysis and mapping of vulnerability and risk of coastal systems to climate change. Available methods on dynamic computer modelling can be divided into sector models and integrated assessment models.

Sector models are those that focus on the analysis of coastal vulnerability related to a particular coastal process (e.g. coastal erosion) and therefore not directly dealing with the evaluation of coastal vulnerability to multiple climate change impacts (e.g. RACE).

Integrated assessment models aim to evaluate the vulnerability of coastal systems to multiple climate change impacts, including the cross-sector analysis of the interaction among different impacts and considering changes in other factors affecting the coastal system. Examples of integrated assessment models considered in this tool include SimCLIM and DIVA.

3.5.2. Risk Assessment of Coastal Erosion (RACE)

3.5.2.1. Introduction

RACE has been included in this chapter as an illustrative example of a sector model since it has been consistently applied at a close-to-national scale to specifically support local and regional adaptative planning.

The aim of the RACE project was to develop, test and disseminate a robust and a consistent probabilistic assessment of hazard and risk of coastal erosion, in the United Kingdom. Co-funded by the UK Department for Environmental Food and Rural Affairs (DEFRA) and the Environmental Agency, the methodology is based on the source-pathway-receptor approach to risk analysis.

RACE is supported by data and information from monitoring programmes and risk-based inspections and must be compatible with the RASP (Risk Assessment of flood and coastal defence for Strategic Planning) method for flood risk assessment.

One of the main reasons for the development of RACE was the need to provide coastal authorities with the means to better understanding appraise and quantify the coastal erosion risk they manage. As such the tools developed are appropriate for application without requiring expert inputs.

Furthermore, outputs should be used to support several issues, namely (Halcrow Group, 2007):

- Informing public safety assessments and planning of necessary improvements;
- Informing the developments of Shoreline Management Plans and strategies for their implementation;
- Informing the development of other regional and local plans and consideration of planning applications;
- The management of coastal cliff instability and erosion risk.

During the project, end-users have been consulted in order to provide essential information that the methodology should have:

- Provide a robust and consistent approach that can be applied by all coastal protection authorities;
- Have the ability to aggregate local results to inform national assessments of coastal cliff instability and erosion risk;
- Use information provided from monitoring programmes and risk-based inspections;
- Include a hierarchy of methods;
- Map of hazards and risks, together with associated probability.

3.5.2.2. General Approach

The basic requirement of the RACE analysis has a fundamental question "how long will it take for an asset to be lost?". One single-approach was adopted, irrespective of scale or data, that comprises three steps (Halcrow Group, 2007):

- What assets are there? Where are they?
- What is the mechanism for the landform to erode? How fast will this occur?
- By how long and how much will any defence delay this process? What is the mechanism for defence failure? What is the chance of this occurring this year?

These components can be demonstrated in Figure 3.5.

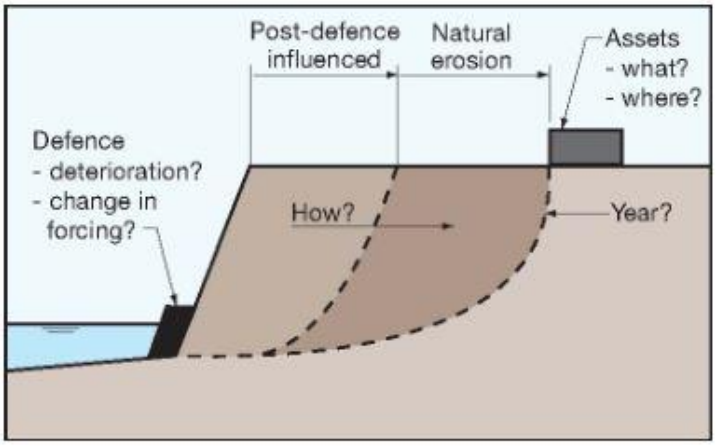


Figure 3.5 - Asset Risk Influences (Halcrow Group, 2007)

Therefore it was determined that the approach to assessing risk could be considered to have three distinct elements:

- assessment of the mechanisms for erosion and defence failure;
- determining hazard as a result of these mechanisms; and
- establishing the consequences, i.e. the risk.

This methodology can be considered in terms of source-pathway-receptor risk model, i.e. the various erosive forces and constraints (sources) are determined and subsequently combined to establish how they propagate to their point of impact, where they become hazard (pathway), before assessing the magnitude of the effect or risk (receptors), as presented in Figure 3.6.

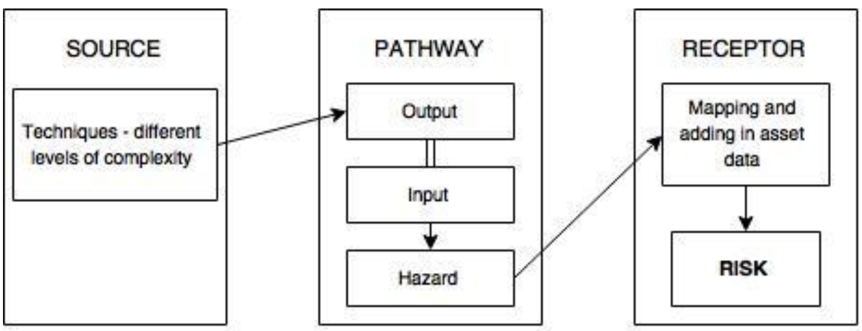


Figure 3.6 - Assessment Framework (Halcrow Group, 2007)

The pathway analysis is presented in Figure 3.7. It shows a typical defence performance and unconstrained erosion curves produced by the initial source data analysis. Also, it indicates other criteria that can be included in the assessment, such as the mode of reaction of the coastline pos-defence failure.

At this stage, there is a provision for the user to intervene to check the result and, if necessary, return to the previous stage to vary the analysis criteria and produce an improved prediction. There is also provision for the user to make certain choices, such as the format of the final output that is required - for example, whether the output is required **as the probability for a certain point** or the **probability for a certain year**.

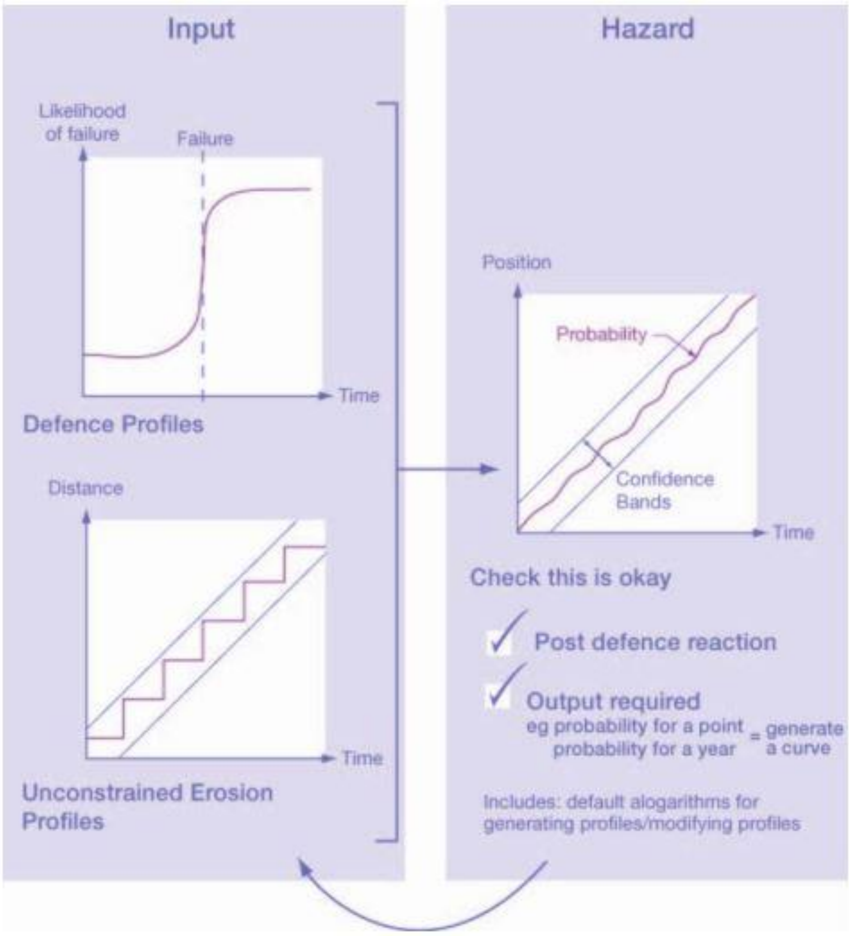


Figure 3.7 - Pathway analysis (Halcrow Group, 2007)

The scale of output that can be produced by the methodology is variable. It gives results nationally, regionally, locally, for an individual asset, for instance a single property or feature of interest such as a power station. The output can be given in two forms: numerical and spatial (Halcrow Group, 2007).

Numerical outputs might take several forms, which stands out:

- total number of assets at risk over time;
- value of assets at risk over time;
- probability of an asset/ group of assets being lost;
- average annual risk;
- time until an asset is lost;

- individual/ societal risk.

Spatial, or mapping output might also take a number of forms, including:

- lines/zones of equal probability, although these would necessarily relate only to one point in time as this probability varies year-on-year;
- future shoreline positions;
- probability mapping relating to the assets themselves, which itself might take different forms, e.g. the probability of being lost by a particular time.

3.5.2.3. Source Data Analysis

In order to assess the potential failure of coastal defences and the natural erosion rate, the authors identified many techniques that might result in the same output. The complexities of the technique employed depend on the economic value, data availability and accuracy required (Ramieri *et al.*, 2011).

Figure 3.8 illustrates one kind of output that the end-user can produce from the source analysis, which will be further necessary to the hazard assessment.

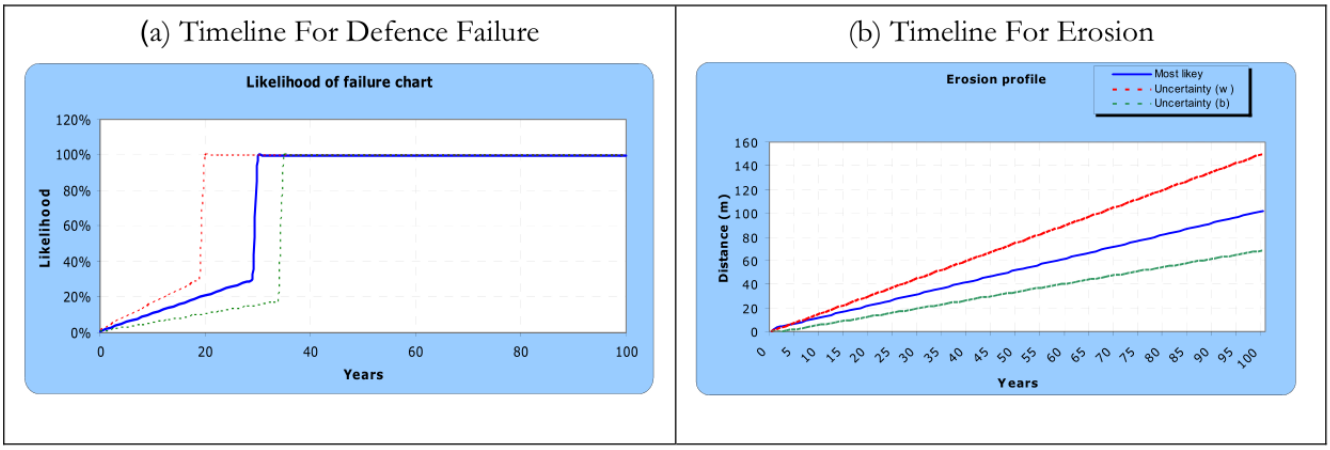


Figure 3.8 - Timelines for (a) defence failure, and (b) natural erosion processes for an indicative stretch of coastline (Ramieri *et al.*, 2011)

In the case of figure 3.8 (a), the user assesses the most likely time of failure of a coastal defence to be in 30 years, but collapse might occur as early as 20 years, or as late as 35 years. In the period before failure, there is still a chance of 1% per year (+/- 0.5%) of storm conditions that exceed the design specifications of the defences. The probability of failure of the coastal defences is also compared to the user's assessment of erosion of the coastline without defences, Figure 3.8 (b). In the included example, this is estimated at between 70 m and 150 m in 100 years, with a most likely estimate of 100 m (Ramieri *et al.*, 2011).

A general framework has been developed for assessing the probability of coastal erosion. Two general factors were considered when taking into account the influence of coastal defences (Halcrow Group, 2007):

- general deterioration of the defence over time;
- failure of the defence due to design conditions being exceeded, e.g. destroyed by a storm, or undermined by falling beach levels.

Deterioration can be addressed based upon defence type and condition, derived from generic assumptions or thorough detailed calculation that derives the same form of output, namely a timeline. Considering failures resulting from changes in forcing conditions, then there is an annual probability of exceedance and thus failure. Trends in forcing conditions can be identified by analysing data from site surveys and past and present conditions affecting a defence structure (Halcrow Group, 2007).

3.5.2.4. Hazard Assessment

A major complication with making risk assessments for coastal erosion is successfully combining information on defence integrity with knowledge of erosion processes.

The hazard assessment considers different erosion scenarios, following failure of coastal defence. This 'post-failure retreat' may differ from natural coastal retreat in two different ways:

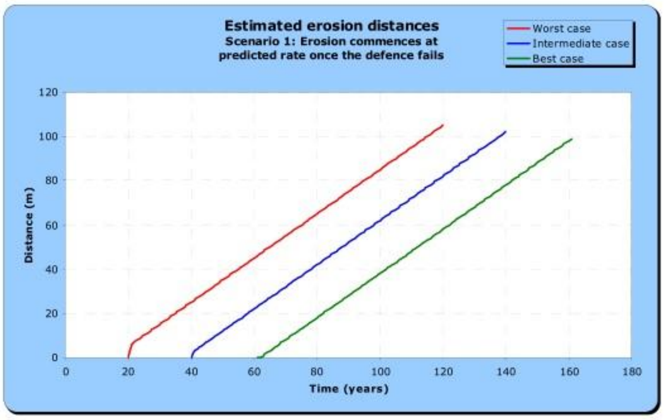
- a rapid (probably non-linear) catch-up process - whereby the erosion of the cliff happens at a much faster rate than the natural rate;
- an initially slow retreat rate, with the residual effects of the failed defences still offering some limited protection, which means that the erosion rate is slower than the natural rate.

Both of these are known factors, but there is virtually no information on either, which makes quantification of the associated times and rates difficult to determine.

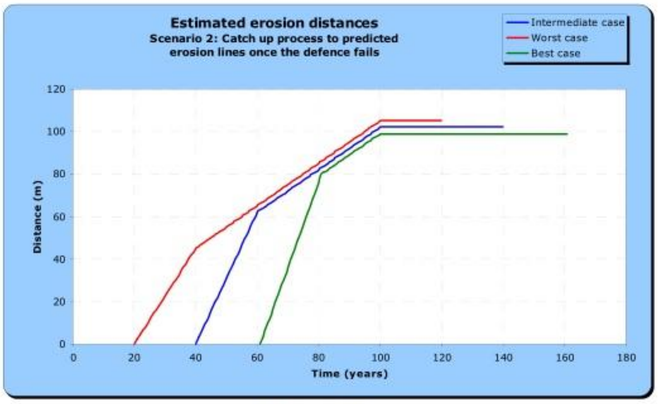
The method provided takes both components of erosion and defence failure probability and combines them to deliver two measures of hazard: **the probability of erosion for a given length** and **the probability of erosion for a given time**. In both cases three defence-erosion scenarios are calculated, with the user determining the most appropriate for their section of coastline (Halcrow Group, 2007):

- Scenario 1 shows the hazard curves considering the onset of potential erosion is simply delayed until the point in time at which the defence fails, Figure 3.9 (a);
- Scenario 2 assumes that the potential erosion line stays in the originally defined position (i.e. starting in year 0) but the onset of actual erosion is delayed until the defence fails followed by a ‘catch up’, which would be a straight line up from the zero erosion to meet the (original potential) erosion profile after a set period of time (which the user can define), Figure 3.9 (b);
- Scenario 3 considers the effect on the erosion timeline if the defence had been in place (delaying erosion) for certain period of time. Thus the potential erosion line is shifted back in time to a starting time representative of the age of the defence (the user can specify how old the defence currently is), and once the defence fails there is again a catch up period that the user can define, Figure 3.9 (c).

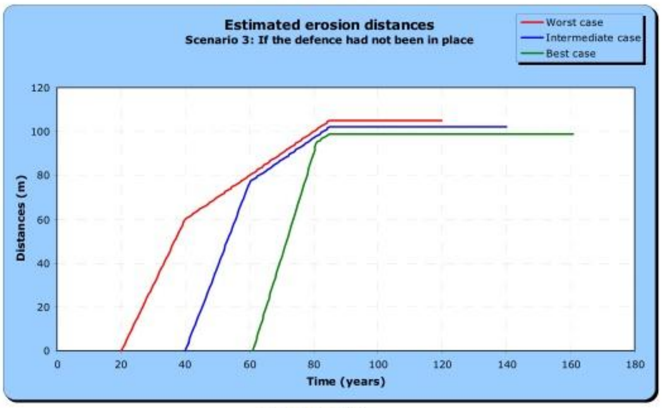
Figure 3.9 shows all scenarios calculated to produce an envelope of probabilities, namely best and worst cases and intermediate, most likely case (Halcrow Group, 2007).



a) Scenario 1



b) Scenario 2



c) Scenario 3

Figure 3.9 - Erosion Scenarios with Defence Influence (Halcrow Group, 2007)

Further to these assumptions of post-failure retreat, probabilities of erosion were calculated for a particular location over time, and probabilities of erosion at a certain distance from the coast for a given time period. This approach helps to identify the probability of damage to certain locations over time and it is presented in Figures 3.10 and 3.11.

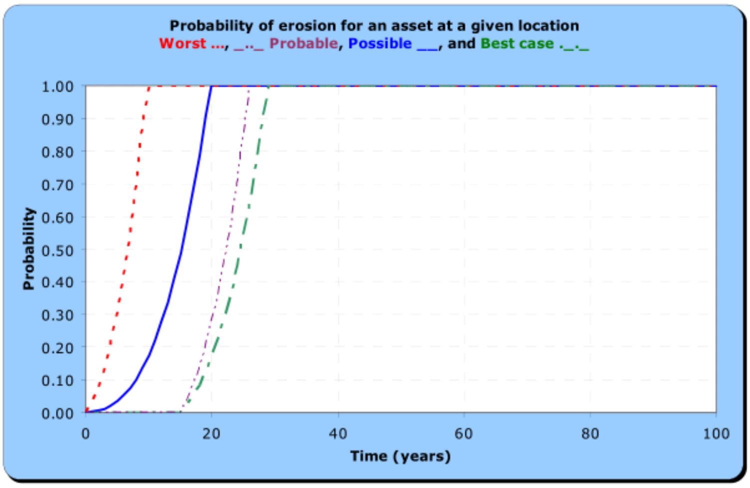


Figure 3.10 - Probability of erosion for a given distance (Halcrow Group, 2007)

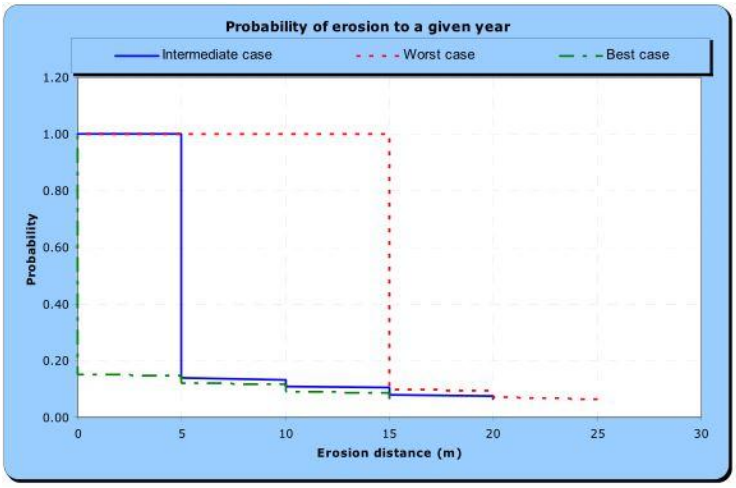


Figure 3.11 - Probability of erosion for a given time and distance (Halcrow Group, 2007)

3.5.2.5. Risk Assessment

The risk assessment done in RACE project is simple and it only characterizes the risk level per asset.

Asset information is available in different forms and may have a variety of attributed data. Figure 3.12 shows spatially information about the assets risk calculation. Risk, for the developers of RACE, is the combination of the hazard assessment with information on consequences, e.g. the loss of particular assets, Figure 3.13.

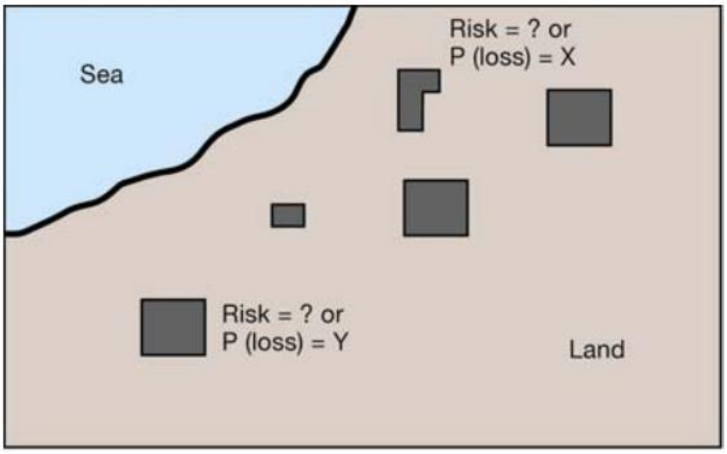


Figure 3.12 - Example of a risk map portraying the risk loss of an asset (Halcrow Group, 2007)

One of the abilities identified by the authors to quantify risk is the knowledge of the relationship between coastline position, time and probability of change.

The assessment of probability of erosion for a given distance enables the risk for any asset to be established. The assessment of probability of erosion for a given time enables an assessment of multiple assets through assessing the probability for a range of timescales. These outputs are best illustrated through mapping results as follows:

- lines/zones of equal probability of loss, relating to a defined point in time (as this probability varies year-on-year), Figure 3.13;
- future shoreline position, Figure 3.14.

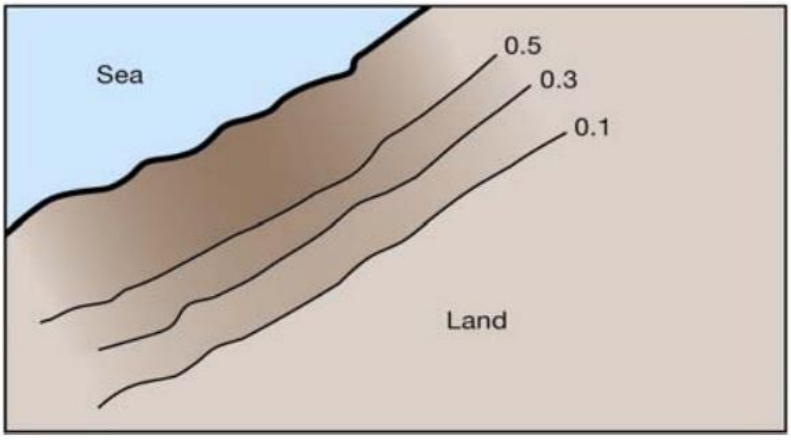


Figure 3.13 - Mapping Output - Zones of equal probability of loss (Halcrow Group, 2007)

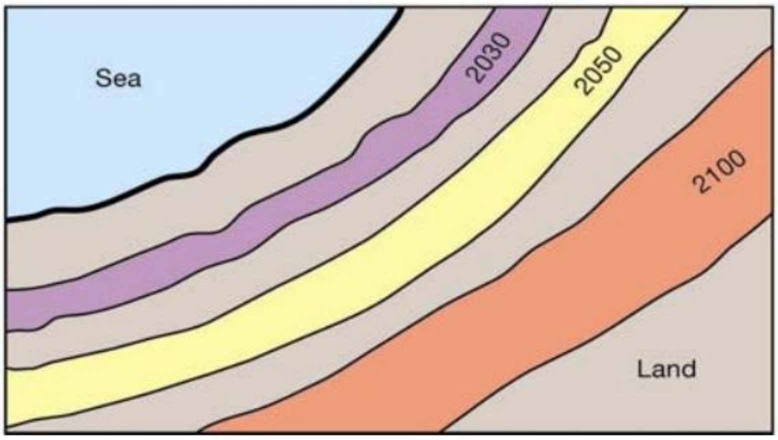


Figure 3.14 - Mapping Output - Future shoreline position (Halcrow Group, 2007)

The ability to produce risk assessments from the hazard assessments has been tested through the project and the methods that have been developed are to be used for production of the forthcoming National Coastal Erosion Risk Mapping (Halcrow Group, 2007).

In conclusion, the techniques developed can be applied to any scale, from assessment for a single section of the coast, to national scope. The method is to be applied to produce the National Costal Erosion Risk Mapping.

3.5.3. SimCLIM and CoastCLIM

The Simulator of Climate Change Risks and Adaptation Initiatives (SimCLIM) Open Framework Software System is tool to aid decision-making under changed climate conditions. SimCLIM is the generic name of the "open-framework" system developed from a “hard-wired” system originally built for New Zealand (Warrick *et al.*, 2005).

The core features of SimCLIM that are directly relevant to risk-based climate impact assessments are its scenario generator and extreme event analyser.

SimCLIM is a modelling system software used to link and integrate complex arrays of data and models in order to simulate (both temporarily and spatially) bio-physical impacts and socio-economic effects of climate variability and change, including extreme climate events. In this way, it provides the foundation for assessing options for adapting the changes and reducing the risks (Ramieri *et al.*, 2011).

Other authors further refer that SimCLIM enables examination of potential erosion and flooding in response to future climate scenarios including sea-level rise. Its coastal subroutine involves an erosion model that is a modified version of the Bruun rule (Abuodha and Woodroffe, 2006).

SimCLIM is designed to support decision-making and climate proofing in a wide range of situations where climate and climate change pose risk and uncertainty. The probabilities and return periods for such extreme events can also be queried for the future using an array of future scenarios of climate change, as the ones released by the IPCC (Abuodha and Woodroffe, 2006).

The "open-framework" features are relatively recent (Warrick *et al.*, 2005) and are a distinctive advantage of SimCLIM, as they afford users the flexibility for importing their own data, customizing the system for their own purposes - much like a GIS. The geographical size is a matter of user choice (from global to local), as is the spatial resolution (subject to computational demands and data availability) (Warrick, 2009).

As its core, SimCLIM contains a "scenario generator" which uses a "pattern scaling" method (Carter *et al.*, 2001, Hulme *et al.*, 2000, Santer, 1990) that involves the scaling of "standardised" spatial patterns of climate change from very complex General Circulation Models (or GCMs) by the time-dependent (e.g. year-by-year) projections of global-mean climate changes (Ramieri *et al.*, 2011).

There are tools to allow the user to import (Ramieri *et al.*, 2011):

i. spatially-interpolated climatology and other spatial data (e.g. elevation surface);
ii. site time-series data;
iii. patterns of climate and sea-level changes from General Circulation Models;
iv. impact models that are driven by climate variables;
v. shape files (boundaries, roads, streams).

As illustrated in the Figure 3.15, SimCLIM has a vertically-integrated, "top-down" structure that links global, local and sectoral modes and data for the purpose of examining impacts on, for example, agriculture, health, coasts or water resources (Warrick and Cox, 2007).

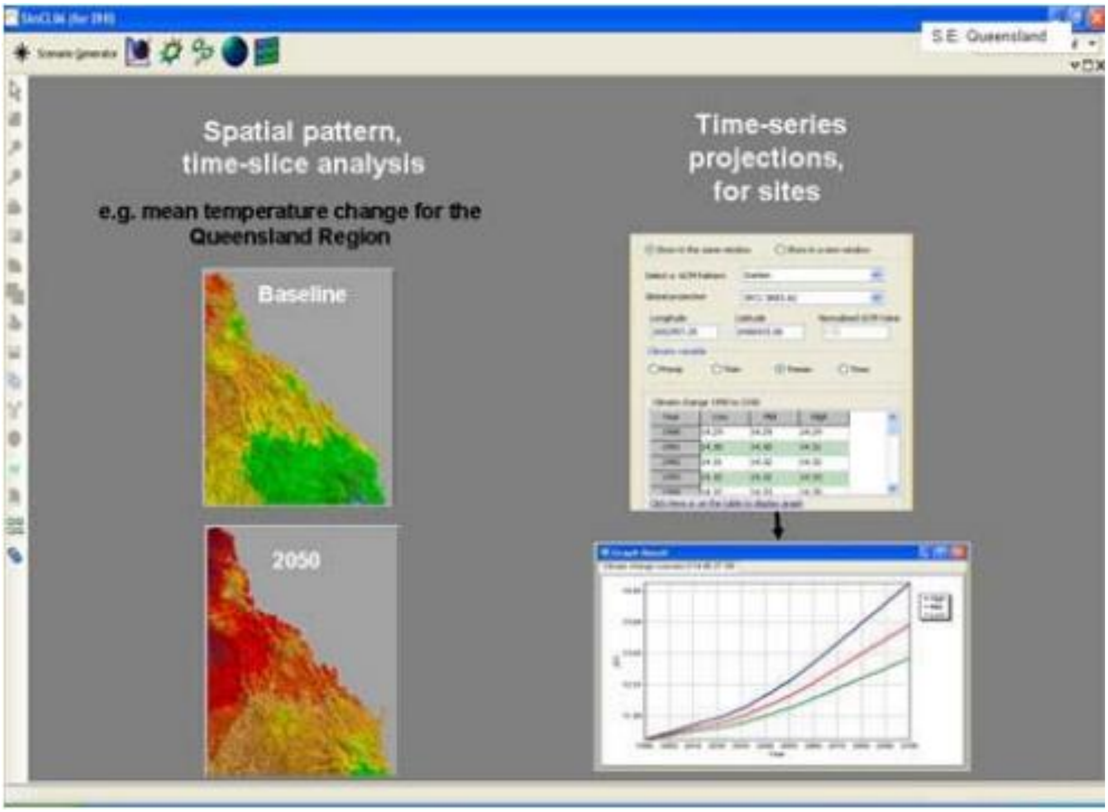


Figure 3.15 - Example of spatial and site time-series projections produced by SlimCLIM scenario generator (Warrick, 2009)

The SimCLIM user interface provides the user with considerable scope for choosing amongst global projections, General Circulation Model's patterns, model sensitivity values and future time horizons (Ramieri *et al.*, 2011).

One of the distinct advantages of using the generator is that it allows rapid generation of place-based sea level scenarios, which accounts for some uncertainties associated with emissions scenario (Kay and Travers, 2008).

The coastal flood model is spatial and allows the user to examine changes in the areas of potential inundation from the combined effects of sea-level rise and extreme storm events. SimCLIM would have seem to have considerable potential for application for further validation on other parts of the coast, particularly those that do not show a consistent trend of shoreline displacement (Ramieri *et al.*, 2011).

The CoastCLIM software enables a wide range of potential users to examine future climate scenarios in the context of their particular sectoral interests. The method features a separate sea-level generator to calculate sea-level change due to climate change and global warming in association with that resulting from local land movements (Abuodha and Woodroffe, 2006).

In the Figure 3.16, an example of Application of CoastCLIM in Western Australia is shown. CoastCLIM is an integrated assessment model for climate change impact on shoreline position that forms a component of SimCLIM. CoastCLIM is a simulation model of shoreline changes for beach and dune systems based on a variant of the Brunn's Rule, enabling "what if" scenarios in coarse temporal and spatial scales.

Initial data inputs into the model are:

- shoreline response time (to storms and sea-level rise) in years;
- closure distance from the shoreline (m);
- depth of material exchange or closure depth (m);
- dune height (m);
- and residual shoreline movement (m/year).

Using 'what if' scenarios for the inputs and varying the input values, different types of graphs can obtain as shown in Figure 3.16 on the right. The current shoreline after varying different inputs is shown in Figure 3.16 on the left.

Patterns of regional sea-level variation can be derived from Global Circulation Models (GCM's) outputs; these can then be used in conjunction with the coastal simulator. Shoreline position extends historical reconstructions, as shown in Figure 3.16.

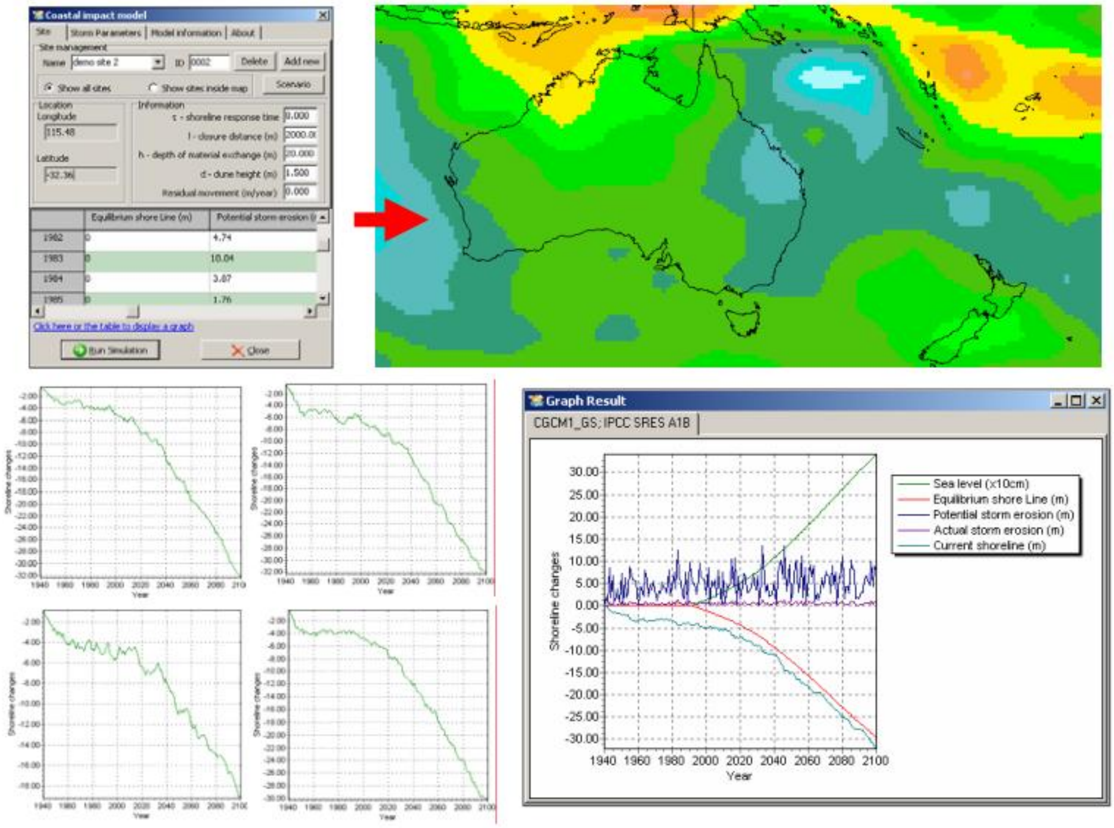


Figure 3.16 - Output for demo site 2, in Western Australia generated for CoastCLIM version 0.1 (Abuodha and Woodroffe, 2006)

Abuodha and Woodroffe (2006) concluded that CoastCLIM has considerable potential for application in Australia. The demonstration from the Western Australian coast indicates the ability of the model to generate trends that are similar to historical patterns, but further validation on other parts of the Australian coast, particularly those that do not show a consistent trend of shoreline displacement.

3.5.4. DIVA

3.5.4.1. Introduction

DIVA or Dynamic Interactive Vulnerability Assessment is a user-friendly tool developed by the EU funded consortium DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise.

It is an interdisciplinary methodology in the form of a flexible assessment tool, which will enable its users to produce quantitative information on a range of coastal vulnerability indicators and to analyse a range of mitigation and adaptation policies (Hinkel and Klein, 2003).

The quantitative information produced covers a range of coastal impacts and adaptation indicators; however it is only addressed to national, regional and global scales. In the next sub-chapters it will be made a description of DIVA method, its tool and an example of application.

3.5.4.2. The DIVA Method

The DIVA method consists of two parts: a modelling framework and a semi-automated development process. The modelling framework frames the model to be built by providing a general a priori conceptualization of the system to be modelled. The development process facilitates the integration on the process level. It frames the iterative specializing of the framework's general concepts to the needs of the specific problem addressed (Hinkel, 2005).

Thus, the modelling framework provides concepts for expressing information about the system, as well as concepts for representing the system's dynamics.

The geographic features represent the real-world entities such as regions, countries and river basins. The dynamics of the system is represented in the form of first-order difference equations (Hinkel and Klein, 2009).

The **development process** organizes the integration of knowledge about the system that enters in the process in four ways, represented in Figure 3.17 (Hinkel and Klein, 2009):

- the **ontology**, which is a shared language to talk about the system to be modelled;
- the **algorithms**, which represent the system's dynamics;
- the **data**, which represent the initial state of the system and the scenarios that represent the system's possible future evolutions;
- the **use-cases**, which specify how the user can interact with the model via Guided User Interface.

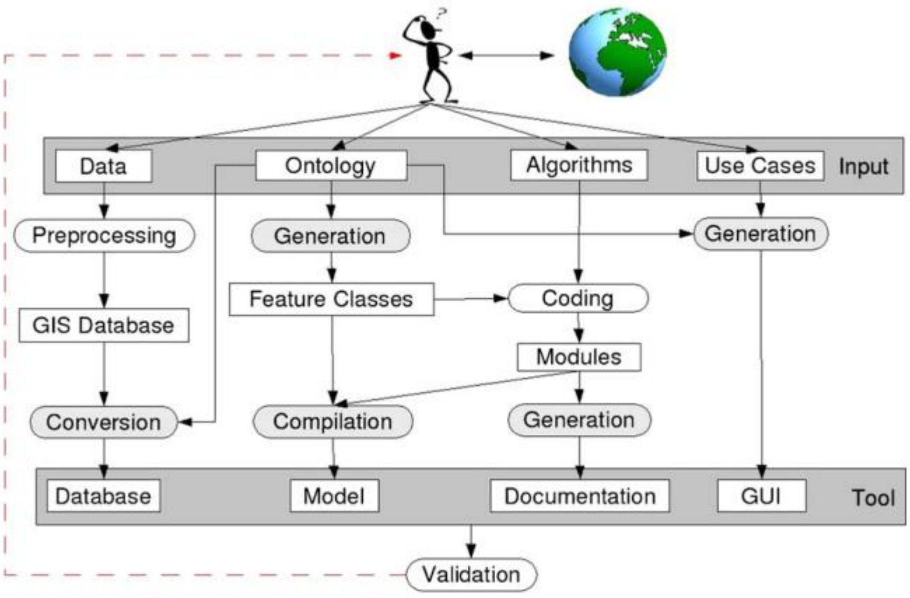


Figure 3.17 - The development process of DIVA method (Hinkel and Klein, 2009)

An ontology is a specification of conceptualization (Gruber, 1993) that is a list of terms and their definitions. Elaborating a shared ontology means that the geographic features, properties and relations that constitute the modelled system must be specified.

Once the knowledge has entered the development process, most subsequent processes are automated and model development proceeds in three parallel tracks:

- the database development;

- the GUI development;
- the algorithm development.

The **database development** consists of two steps. First, raw data must be pre-processed to fit the ontology. Second, the pre-processed data is automatically converted into the DIVA database format (Vafeidis *et al.*, 2008).

The last step of any iteration of the development process involves the analysis of the modules and their linkages, and the validation of the complete model.

3.5.4.3. The DIVA Tool

Components

The DIVA method was applied to develop DIVA tool. The DIVA tool comprises four main components (Hinkel and Klein, 2009):

- a **detailed global coastal database** regarding biophysical and socio-economic data;
- an **integrated model**, consisting of interacting modules that assess biophysical and socio-economic impacts and the potential effects and costs of adaptation;
- a **graphical user interface** (GUI) for selecting data and scenarios, running model simulations and analysing the results.

The database contains information on roughly 80 biophysical and socio-economic parameters of the world's coasts. Data is represented in 5 x 5 degree grid cells on the basis of seven different types of geographic features: coastline segments, administrative units, countries, rivers, tidal basins, world heritage sites.

The scenarios that drive the model contain information about sea-level rise, land-use change and socio-economic development (i.e. population and economic growth) and derived from the scenarios of the IPCC Special Report on Emission Scenarios (SRES).

The model computes the impacts of sea-level rise on natural and human systems, as well as the effects of human adaptation on these impacts. Table 3.11 lists all modules

Table 3.11 - The modules in DIVA 2.0.3 (Hinkel and Klein, 2009)

Module name	**Description**
Relative sea-level rise	Creates sea-level rise scenarios by adding vertical land movement to the climate-induced sea-level rise scenarios.
River effect	Calculates the distance from the river mouth over which variations in sea level are noticeable.
Indirect erosion	Calculates the loss of land, the loss of sand and the demand for nourishment due to indirect erosion in tidal basins. This is a reduced version of the Delft Hydraulics ASMITA (Stive *et al.*, 1998)
Total erosion	Calculates direct erosion on the open coast based on the Bruun rule. Sums up direct erosion and indirect erosion for the open coast, including the effects of nourishment were applied.
Wetland change	Calculates area change due to sea-level rise, sea dike construction and possible wetland nourishment where applied.
Flooding	Calculates flooding due to sea-level rise and storm surges, taking into account sea dikes.
Wetland valuation	Calculates the value of different wetland types as a function of GDP, population density and wetland area.
Tourism	Calculates number of tourists per country.
Cost and adaptation	Calculates socio-economic impacts of geodynamic effects, taking into account present and/or user-defined adaptation options.

The graphical user interface (GUI) of the DIVA tool enables its users to choose scenarios and adaptation strategies, to run the model, and to analyse and compare the results for different regions, time steps, scenarios and adaptation strategies. The GUI was built on the basis of the Delft Tools, which is a collection of software components for decision support and temporal-spatial data analysis.

Input and output data can be visualized in the form of tables, graphs, charts, and maps. All data used by the model can be edited, imported from spreadsheets or exported to standard Office formats.

Integrated Model

The integrated DIVA model first produces relative sea-level scenarios by combining the sea-level scenarios from CLIMBER-2 with the vertical land movement. With the relative sea-level scenarios as input some types of biophysical impacts as land loss and flooding can be assessed. Land is lost due to submergence and coastal erosion. Both direct and indirect coastal erosion are considered.

The direct effect of sea-level rise on **coastal erosion** is estimated using the Bruun rule (Zhang *et al.*, 2004). This indirect erosion is obtained using a simplified version of the ASMITA (Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast) (Stive *et al.*, 1998).

The **flooding** of the coastal zone caused by sea-level rise and associated storm surges is assessed for both sea and river floods. Taking into account the effects of dikes, flood areas for return periods from 1-in-1 and 1-in-1000 years (Hinkel and Klein, 2009).

DIVA also assesses the social and economic consequences of the physical impacts described above, taking account socio-economic scenarios. Social consequences or impacts are expressed by three indicators. The coastal floodplain population gives the number of people that live below the 1000-year storm-surge level. The indicator people actually flooded gives the expected number of people subject to annual flooding. The indicator forced migration gives the number of people that have to migrate from land that would be permanently lost due to erosion and submergence.

The economic consequences are expressed in terms of damage costs and adaptation costs. For the calculation of damage costs, the above biophysical and social impacts have been valued. The cost of land loss is calculated based on the assumption that all land lost was used for agriculture. The cost of floods is calculated as the expected value of damage caused by sea and river floods based on land-use and a damage function logistic in flood depth.

Adaptation costs are calculated for all of the above adaptation options (i.e. dike building, beach nourishment, tidal nourishment and wetland nourishment).

DIVA implements the adaptation options according to various complementary adaptation strategies. An adaptation has to be selected for each of the four adaptation options (i.e. beach, tidal and wetland nourishment and dike building). The simplest strategy is 'no adaptation', in which DIVA only computes potential impacts. For beach, tidal and wetland nourishment, there is a 'full protection' strategy. For dike building, the equivalent strategy is the 'constant protection' (Hinkel and Klein, 2009).

3.5.4.4. Application of DIVA tool

In this sub-chapter some results of the DIVA tool application at a global scale taken by Hinkel and Klein (2009) will be presented. The impact estimated was the floodplain population (the number of people living below the once-per-1000-years storm surge level) and the expected number of people subject to annual flooding.

The results of both were then compared (however indirectly, due to the differences on scenarios and definitions of impact indicators) to the results obtained by the application of Global Vulnerability taken by (Hoozemans *et al.*, 1993).

The results produced by DIVA are based on a consistent combination of sea-level rise and socio-economic scenarios (including Gross Domestic Product (GDP) and land-use change) both derived from SRES scenarios. Figure 3.18 shows one type of result (at global scale) of DIVA tool where the curves represent the expected number of people subject to annual flooding ("people actually flooded") between 2000 and 2100 for three different scenarios of SRES and adaptation strategies.

DIVA produces results for every 5-year period with the smallest spatial resolution being more than 2000 sub-national administration units.

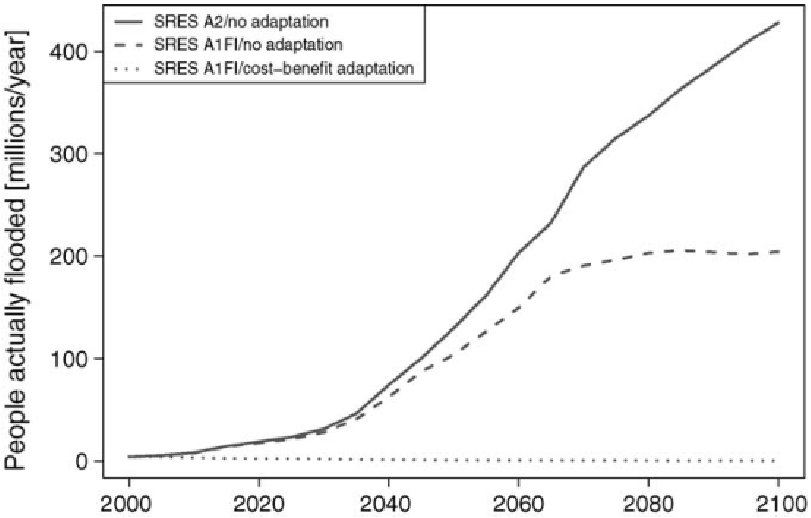


Figure 3.18 - Expected number of people subject to annual flooding (3 different scenarios) (Hinkel and Klein, 2009)

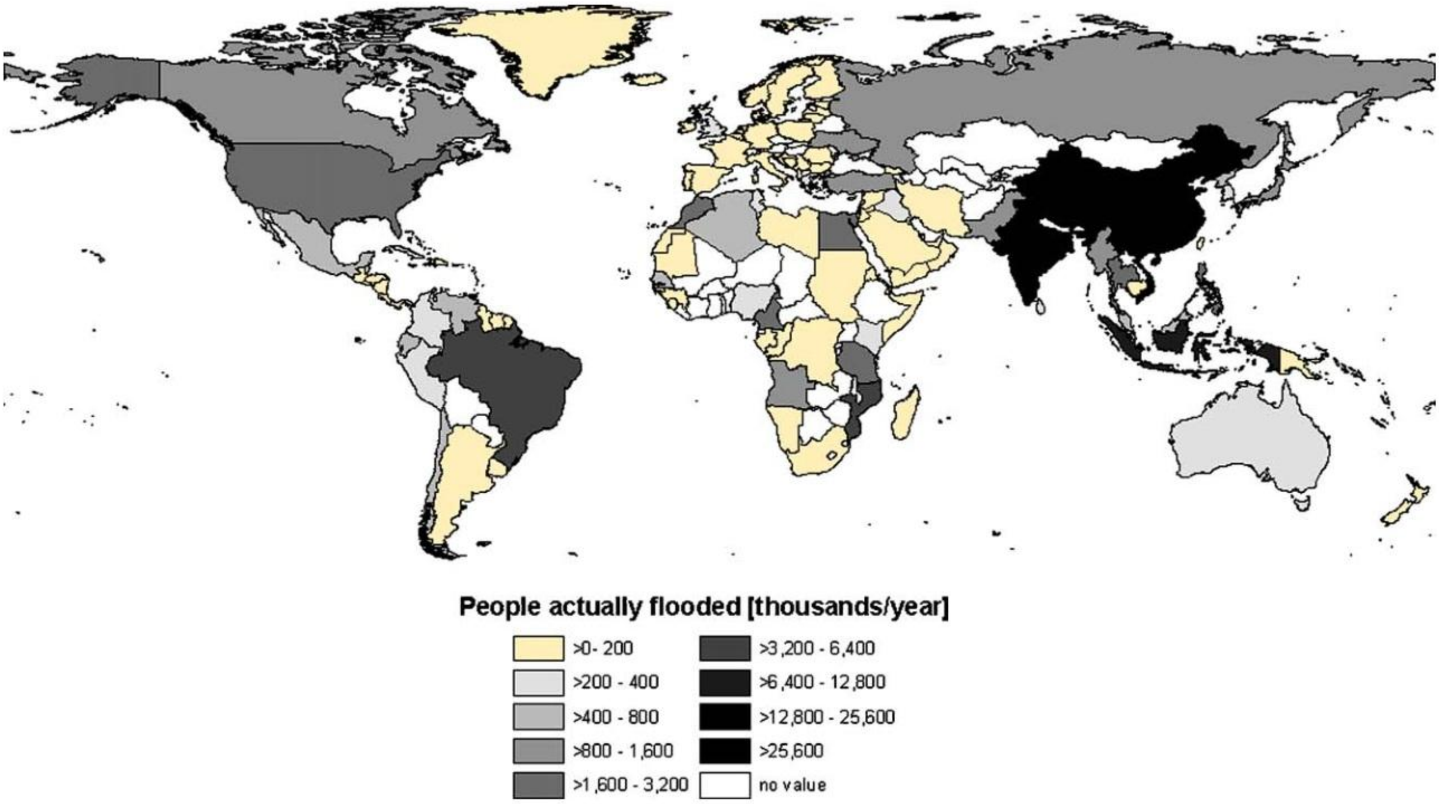


Figure 3.19 - Global application of DIVA, results for expected number of people subject to annual flooding in 2100 under SRES A1F1 scenario and no adaptation measures being taken (Hinkel and Klein, 2009)

DIVA offers a great variety of additional impact indicators, such as land loss, people migrated, annual tourist values. Monetary values are placed on some of these impacts, as well as on the costs and benefits of measures to protect against erosion, flooding, wetland change and salinity intrusion impacts.

3.6. GIS-BASED DECISION SUPPORT SYSTEMS

This group of methodologies, commonly referred as GIS-based Decision Support Systems are increasingly being developed to assist policy-makers in selecting a adaptation assessment. They have an important role for

Also, they support decision makers in a sustainable management of natural resources and in the definition of mitigation and adaptation measures.

3.6.1. DSS DESYCO

3.6.1.1. Introduction

DESYCO, or Decision Support System for Coastal climate change impact, was developed by the Euro-Mediterranean Centre for Climate Change, in order to assess and manage multiple climate change impacts on coastal areas and related ecosystems (e.g. beaches; wetlands; forests; protected areas; groundwater, urban and agricultural areas) at the national/sub-national scale.

DESYCO is a Decision Support System (DSS) aimed at the integrated assessment of multiple climate change impacts on vulnerable coastal systems. It is an open source software that combines different scenarios data (e.g. raster or shapefiles) resulting from climate models (e.g. global and regional climate projections) and high resolution models with vulnerability analysis of environmental and socio-economic features of the territory, in order to provide GIS-based maps identifying hot-spot areas and receptors at risk from climate change (Torresan *et al.*, 2013).

DESYCO adopts an ecosystem approach and implements a Regional Risk Assessment (RRA) methodology, based on a Multi-Criteria Decision Analysis (MCDA), in order to prioritize areas and targets at risk from climate change, and to support coastal communities in planning appropriate adaptation measures (Torresan *et al.*, 2013).

Based on outputs from climate, hydrodynamic, hydrological, hydrogeological and biogeochemical models, the Risk Assessment methodology integrates climate change hazards' analysis with vulnerability analysis of environmental and socio-economic features of the territory.

The final output of the tool are GIS-based maps, providing spatially resolved information about downscaled climate change hazard scenarios and regional/local susceptibility, risks and damages (Torresan *et al.*, 2013).

Examples of coastal study cases of DESYCO are: zone of the North Adriatic Sea (Italy) and Gulf of Gabès (Tunisia).

3.6.1.2. APPROACH

Following, it will be presented a brief description of the main components and functionalities of DESYCO DSS and RRA methodology.

The structure of DESYCO is composed by four main components:

- geo-database for the storage of bio-physical and socio-economic data for the study areas;
- multi-scale scenarios provided by numerical models simulations or time series analysis;
- a Relative Risk Model (RRM) that integrates Multi-Criteria Decision Analysis techniques for the application of the RRA methodology;

- a Graphical User Interface (GUI) that facilitates the interaction of the final user with the system and simplify its understanding.

Torresan *et al.* (2013) lists some of the possible outputs when applying DESYCO:

- investigate impacts associated to different climate change scenarios and sensitive targets;
- identify and prioritize targets and areas susceptible to or at risk from different climate change impacts in the considered study area;
- produce interactive GIS-based maps (i.e. exposure, susceptibility, risk and damage maps) for different natural and human receptors (e.g. beaches, wetlands, natural environments, urban and agricultural areas);
- transfer information about potential climate change impacts to support the development of sustainable adaptation actions.

The characterization of the land, land/sea vulnerability, and the construction of susceptibility, risk and damage maps, involve the identification and application of a range of vulnerability indicators and indices, representing the sensitivity of the coastal communities, systems or assets, to the damaging effects of climate change hazards (Torresan *et al.*, 2008).

Particularly in the early stages of its development, DESYCO consisted in the identification of vulnerability indicators and indices for the evaluation of the climate change impacts in coastal zones. Before analyzing the risk, the first step of RRA in DESYCO considers a series of impacted systems and/or resources for which a matrix of vulnerability indicators can be built.

Furthermore, combined indices, which represent the sensitivity of the coast to the damaging effects of climate change hazards, can be built accounting for different systems or sectors (termed "receptors"). Such indicators or indices can be selected from datasets related to fields such as geomorphology, ecology, biology and socio-economic (Ramieri *et al.*, 2011).

Within the RRA, vulnerability indicators or indices are classified in four main categories of factors (Torresan *et al.*, 2013):

- **Susceptibility Factors** (SF) describe the degree to which a receptor is affected either adversely or beneficially, by climate-related effects;
- **Value Factors** (VF) identify relevant environmental and socio-economic values of the receptors that need to be preserved for the interest of the community (e.g. land use, fishing areas, crop economic value, population density);
- **Pathway Factors** (PF) are physical characteristics of the receptors which determine their exposure to climate change hazards (e.g. elevation, distance from coastline, soil permeability);
- **Attenuation factors** (AF) are factors that can attenuate the intensity of the hazard associated with an impact, for instance: an artificial structure (e.g. a dike) able to reduce the hazard related to a storm surge flooding or to coastal erosion.

Vulnerability indicators description had as a scientific base the , namely the first three one's (SF, VF and PF) and the contribution of Torresan *et al.* (2013) related with the latest Attenuation Factors (AF).

In order to represent potentially significant hazard scenarios at the regional scale and built climate change exposure maps to be used in the risk assessment, a chain of models was set up for the study areas referred on the introduction of DESYCO. This chain includes different types and spatial scales of numerical models simulating relevant circulation and morphodynamic processes recognized as influencing climate change impacts on coastal areas, ranging from models reproducing atmosphere and ocean dynamics to models simulating relevant circulation and biogeochemical processes in coastal waters.

The single outputs from the multi-model chain are called hazard metrics (HM), to be included in the quantitative RRA model (Ramieri *et al.*, 2011). In the RRA, vulnerability indicators and HM are combined for estimating risks and damages related to each receptor, according to the following equations:

$$R_{j,ks} = f_1\lfloor E_{(k,s)}, S_{(j,k)}\rfloor$$

where:

- $E_{k,s}$= exposure related to the impact *k* and scenario *s*;
- $S_{j,k}$= susceptibility of the receptor *j* to the impact *k*;
- $R_{j,k,s}$ = risk related to the impact *k*, an exposure $E_{k,s}$ and a susceptibility $S_{j,k}$;

and

$$D_{j,k,s} = f_2\lfloor R_{(j,k,s)}, Va_{(j,k)}\rfloor$$

where:

- $D_{j,k,s}$ = damage related to the impact *k*, an risk $R_{j,k,s}$ and a value $Va_{j,k}$.

The exposure function $E_{k,s}$ is an impact specific function aggregating $HM_{(k,s)}$ for the scenario *s* and the impact *k* with the $PF_{(j,k)}$ associated to the receptor *j* and the impact *k*.

For impacts affecting the terrestrial environment (e.g. sea level rise inundation, storm surge flooding) the exposure function is used to project the information provided by sea water models inland.

The susceptibility and the values functions ($S_{j,k}$ and $Va_{j,k}$) aggregate $SF_{(j,k)}$ and $VF_{(j,k)}$ related to the receptor *j* and the impact *k* using specific MCDA functions made available by the model.

Furthermore, vulnerability thresholds to be applied to the selected indicators, as well as methods for aggregating and weighting the indicators have been identified (Ramieri *et al.*, 2011).

Being an integrated GIS with GIS functionalities based on open source libraries, DESYCO also produce vulnerability maps that allow a quick visualization and comparison of the assessment for different segments of the region.

Figure 3.21 shows the flow of information leading to the production of maps during the different stages of the RRA (Ramieri *et al.*, 2011)

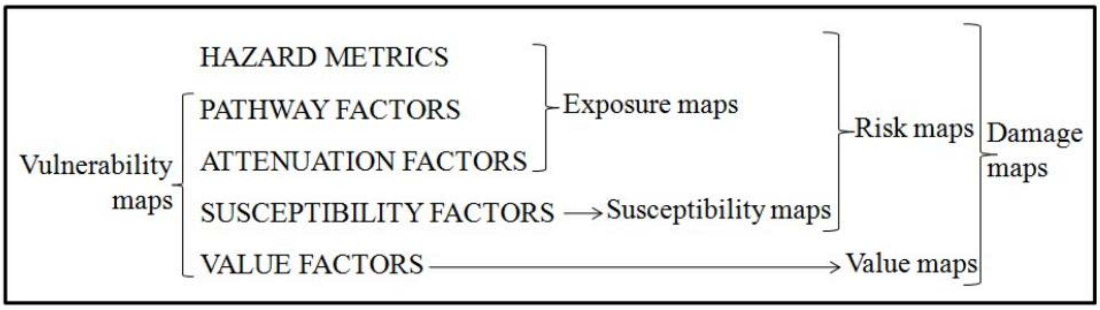


Figure 3.20 - Integration of factors and metrics to produce the cascade of maps from the DESYCO-RRA system (Ramieri *et al.*, 2011).

Trough DESYCO and the related RRA approach, it's possible the application of numerical models used for the construction of climate change scenarios and exposure maps. These have been validated through the comparison with observed data for a control period. Moreover, the feasibility of the system structure and the usability of its interface for end users were tested through stakeholder analysis and user questionnaires. These confirmed the validity of the methodology choices and provided useful recommendations for further improving the DSS framework (Ramieri *et al.*, 2011).

In the RRA model, vulnerability factors and hazard metrics are used to estimate risks and damages related to each receptor, using specific MCDA (Multi-Criteria Decision Making) functions. Accordingly, two-dimensional visualization of exposure, susceptibility, risk and damages, based on raster maps and risk indicators, are produced Torresan *et al.* (2013).

The methodology is therefore composed by the following steps Torresan *et al.* (2012):

- Definition of the regional vulnerability matrix;
- Definition and scoring of vulnerability classes;
- Assignation of weights to vulnerability factors;
- Normalization and classification of vulnerability values;
- Construction of vulnerability maps.

The following explanation is about the DESYCO produced maps (Figure 3.22) for the study case of the North Adriatic Sea (Italy) for the storm surge flooding impact of 174 cm in 2100.

Exposure maps, representing climate change hazard scenarios against which a receptor operates, are presented as a result of the aggregation of hazard metrics, pathway and attenuation factors, Figure 3.22 (a).

Susceptibility maps are derived from the aggregation of susceptibility factors and represent the spatial distribution of geophysical and environmental susceptibility to climate change, Figure 3.22 (b).

Risk maps, Figure 3.22 (c), are obtained from the overlay of exposure and susceptibility maps and enable the identification and ranking of areas and receptors at risk from climate change related impacts in the considered region and according to a selected hazard scenario.

Finally, damage maps derive from the combination of risk and value factors and provide a relative estimation of the potential social, economic and environmental losses, Figure 3.22 (d) (Torresan *et al.*, 2013).

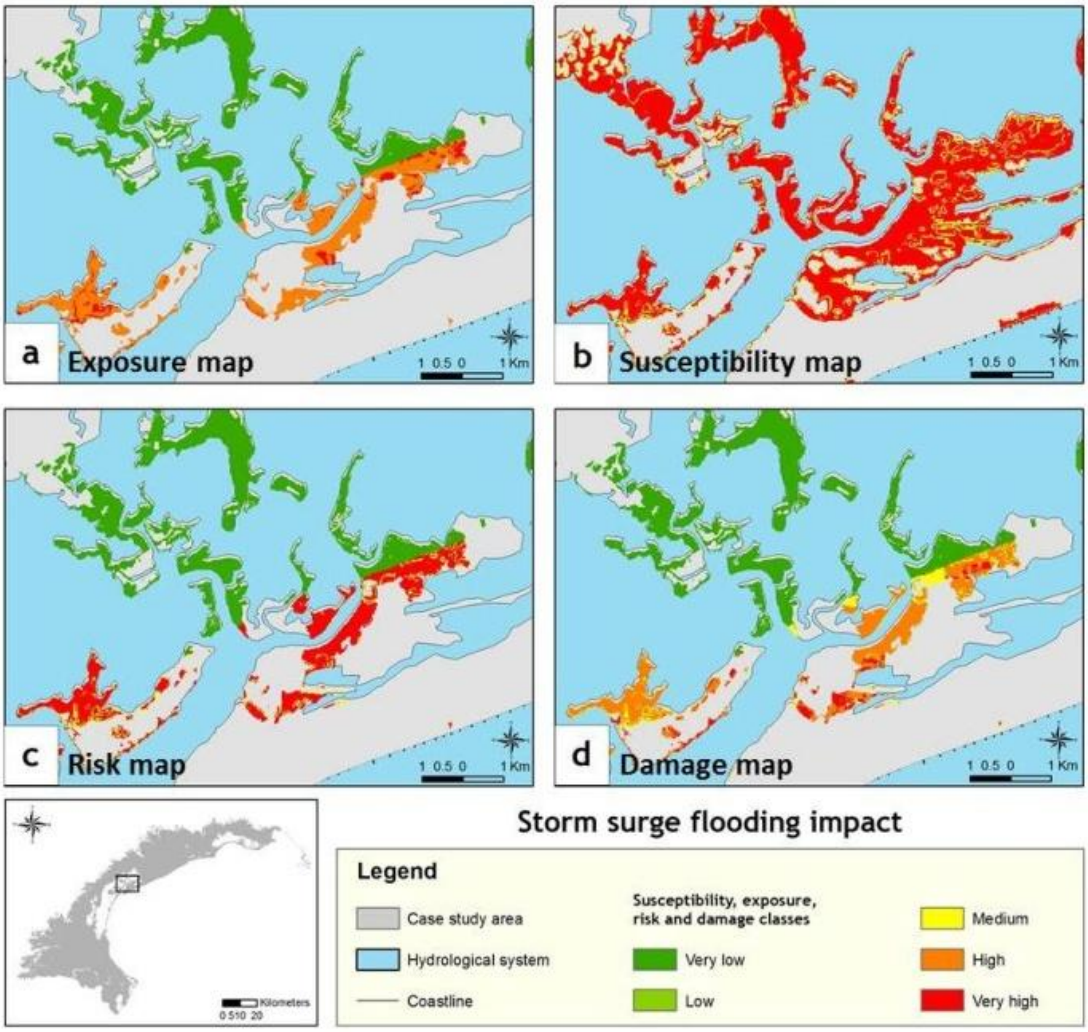


Figure 3.21 - Example of GIS-based maps produced by the DESYCO in the North Adriatic Region: exposure map for a flooding scenario of 174 cm in 2100 (a) susceptibility map (b) risk map (c) and damage map (d) for the receptor protected areas (Torresan *et al.*, 2013)

The main issues and gaps related to the vulnerability-risk assessment procedure offered by DESYCO through the construction maps are:

i. the diversity of data sources, formats, and spatial scales that introduced geographical errors;
ii. the limited availability of well differentiated test areas.

DESYCO's structure is not limited to a fixed suite of models and/or scenarios. Also scaling up the approach requires including less sophisticated schemes in the integrated framework, more simplified parameterisation and fewer detailed input data. Dealing with numerous and heterogeneous data for small extents increases the complexity of simulated impact processes, as well as the analysis of the results. Finally, the tool can be further improved by supplying the models with more complete dataset or adding additional indicators/simulated processes following the increased production and availability of thematic maps.

Ramieri *et al.* (2011) lists two key-points to keep in mind:

- the uncertainty from either input data quality-quantity or model formulation contributes to the final estimation of risk and has to be, as much as possible, quantified;
- the vulnerability-risk classification should not attempt to provide absolute predictions about the impacts of climate change, rather, it is a relative index providing information about the areas within a region that are affected more severely than others.

4
THESEUS - A NEW DECISION SUPPORT SYSTEM

4.1. INTRODUCTION

This chapter introduces the focus of this master thesis, making a presentation of the open-source Spatial Decision Support System (DSS) developed within THESEUS Project. Its main intention is to help decision makers and coastal managers to assess risk across a range of spatial and temporal scales.

THESEUS DSS is one of the most recent tools that pretend to give a complete answer to coastal issues regarding coastal management, development and protection of communities. It has some of the most detailed functionalities ever developed including a high level of resolution risk assessment of the study place, wider range of mitigation options and a Multi-Criteria analysis.

Also, THESEUS is the largest integrated project within coastal risk assessment and mitigation funded by the European Commission.

Zanuttigh *et al.* (2014) define this spatial Decision Support System as a computer-based software tool able to assist decision makers in their decision process, allowing assessing the conditions of a system under a variety of scenarios and the consequences of different adaptation and mitigation measures.

THESEUS DSS integrate the relevant environmental models, databases and assessment tools within a Graphic User Interface (GUI), spatial problems such as flood and erosion risk in a Geographical Information System (GIS) approach.

This Decision Support System is designed to fill a gap among the existing tools, based on its following characteristics:

- Perfect integration across physics, engineering, ecology, spatial sciences and economy fields;
- Spatial planning scales between 10 and 100 km and short, medium and long-term time spans of 1-10-100 years;
- Several types of mitigation options such as engineering defences, ecologically based solutions and socio-economic ones;
- Decision-making based on a balance between deterministic models and expert discussion-based assumptions;
- Open source approach to maximize the availability and uptake the tool.

This chapter is divided in four sub-chapters that describe the following aspects of THESEUS DSS:

1. The modelling framework and the main challenges when describing physical, ecological and human processes, sub-chapter 4.2.
2. The goal of the DSS and the intended application at the Science and Policy Interface (SPI) on 4.3.
3. The technical structure of the DSS in 4.4, including scenarios and mitigation options, and as example, the most significant results where it was firstly applied, Cesenatico, Italy.
4. Some of the limitations of the DSS and challenges in 4.5.

4.2. MODELLING FRAMEWORK

4.2.1. CONCEPTUAL FRAMEWORK

The conceptual model proposed in THESEUS is based on the Source-Pathway-Receptor-Consequence (SPRC) model (FLOODsite, 2009, Narayan *et al.*, 2012, Narayan *et al.*, 2014, Thorne *et al.*, 2007). SPRC model is a 1D-2D conceptual model for representing flood systems and processes that lead to particular flooding consequences.

It represents how the Sources (waves, tides, storm surge, mean sea level, river-discharge, run-off) through the Pathways (coastal defences units) affect the Receptor (buildings, infra-structure, habitats) generating economic, social and environmental Consequences.

Scenarios of change will modify the consequences of flooding and, given adverse trends such as sea-level rise and increasing coastal development, will increase them. Also mitigation options from a wide menu of engineering, ecological and social options can offset this increase in Consequences and keep risk at an acceptable level.

As DINAS-COAST (2004), SAFECOAST (2008) and FLOODsite (2009) approach, THESEUS presents a scenario framework that considers the present situation, and three future scenarios: short (2020’s), medium (2050’s) and long-term (2080’s).

The coastal risk assessment is performed at a high spatial resolution using a Digital Elevation Model (DEM) to support detailed coastal management analysis of receptors, consequences and mitigation.

Sources have been distinguished as primary and secondary (Zanuttigh *et al.*, 2014):

- Primary sources: weather-related phenomena (e.g. precipitation) which generate water that could cause flooding;
- Secondary sources: physical manifestations of the weather-related which may cause flooding e.g. wave, surge and changes in river volume and flow.

Sources are essentially classified into three groups according to duration:

- *Short-term* processes as storm surge, wind waves, tides, run-off due to downpours;
- *Seasonal* as river high/low waters;
- *Long-term* processes as sea-level rise and subsidence.

To define source statistics of the study site, it is necessary to access and compile information provided by research archives like PRUDENCE3 or HIPOCAS4 from IPCC AR4 and new data through a number of hindcast (hindcast refers to a numerical model integration of a historic period where no observations have been assimilated) and downscaling activities from global to local study areas (Weisse *et al.*, 2014).

This approach delivers a picture of present and potential future climate changes in the study sites and provides an assessment of the uncertainties associated with these changes (Zanuttigh *et al.*, 2014).

The climate parameters included in THESEUS projections are (Monbaliu *et al.*, 2014):

i. extreme sea levels and wave heights;
ii. long-term variation of extreme sea level occurrence;
iii. annual frequency of distribution of extreme sea levels for different return periods;
iv. statistics of storm surges;
v. water pressure fields of major flooding events;
vi. and if appropriate, present and extreme river discharges;

Pathways are the routes and processes which are active during a flood event and they include the components of the flood system and management through or over which flood waters flow, such as habitats relevant for coastal protection, hard and soft coastal defences, and infrastructures.

Understanding the interaction between socio-economic and biophysical system components is complex and is subject of ongoing research, because terms, methods, and scales of analysis differ between natural and social sciences and are often not comparable (Adger *et al.*, 2004).

These data have to be related to each other in a way that makes sense for analysing vulnerability in a specific region and society on a scale that is useful for delivering outputs that can be transferred into the decision (Zanuttigh *et al.*, 2014).

Brooks *et al.* (2005) have given some concepts of future development in this subject, namely the needs in identification and quantification of a variety of indicators on different scales to operating vulnerability and resilience and to create vulnerability profiles.

Source-Pathway-Receptor-Consequence process includes the physical, ecological (habitat) and socio-economic aspects of the flood system, as well as an integrated framework that Decision Support System exploits.

4.2.2 Modelling Physical Processes

In this chapter the modelled physical processes considered in this fully integrated Decision Support System, called THESEUS will be analyzed. As the author mentions, a flood model must (Zanuttigh *et al.*, 2014):

i. Predict and represent spatial and temporal characteristics of the flood required by environmental and socio-economical risk assessment procedures, with a particular emphasis on maximum or worst case values of flood characteristics;
ii. Produce runs for several risk assessment scenarios in a short time;
iii. Simulate flooding due to overtopping, overflow and failure of defence measures, including beach retreat;
iv. Be easily embedded inside the open-source DSS developed inside a GIS framework;

There are numerous hydrodynamic models (Bates and Anderson, 1996, Bates and De Roo, 2000, Bates *et al.*, 2005, Bradbrook *et al.*, 2004) that can be used to simulate the propagation of flood water across floodplain areas. However, these models were not applied in THESEUS due to its expensive computationally run, instability problems and time consuming to set up.

Instead, GIS-base flood inundation or flood spreading models (Brown, 2006, Poulter and Halpin, 2008) were easily implemented in the DSS in order to map the extent of flood.

In the current tool THESEUS, GIS-based flood inundation model was developed considering a water flow method, combined with erosion (Zanuttigh *et al.*, 2014). The method follows the marker controlled watershed segmentation algorithm described by Meyer and Beucher (1990) and Soille and Ansoult (1990), which it is possible to produce flood maps for different storm surge levels and multiple sources of flood.

Within THESEUS, the algorithm was modified to include finite water volumes which vary with time. It shows an improvement with respect to the existing bath-tub approach adopted in many similar existing tools (DIVA, RegIS, RAMCO).

The water overflow of sea bank during a flood is evaluated through the procedure described by (Martinelli *et al.*, 2010).

The proposed failure mechanism of the flooding process is given by:

$$(Z_m + Z_r + \eta + R_{u2\%}) - Z_{bank} \geq 0 \tag{4.1}$$

where:

Z_m is the storm surge level;

Z_r is the sea-level induced by climate change effects;

η is the wave set-up;

$R_{u2\%}$ is the wave run-up corresponding to the characteristic value of 2% exceeding probability;

Z_{bank} is the crest height of the sea bank.

Equation 4.1 is based on the following simplified assumptions:

- Non-erodible cross-shore beach profile during the storm;
- Absence of defence breaching against wave and tidal loads.

The wave-run up is computed using the Stockdon *et al.* (2006) approach:

$$R_{u2\%} = 1.1 * \left\{0.35 \tan\beta (H_s L_0)^{1/2} + 0.5[H_0 L_0 (0.563 \tan\beta^2 + 0.004)]^{1/2}\right\} \tag{4.2}$$

where:

H_s is the local transmitted significant wave height;

L_0 is the local peak wave length;

β is the beach slope.

The "off-shore" boundary condition is thus moved to the "sea bank line" where the boundary conditions consider a varying level in time W(t) given by equation 4.2. The flood level W(t) is integrated on coastal segments in time to provide water volumes as input data for the flood model (Zanuttigh *et al.*, 2014).

THESEUS DSS is one of few tools that consider the effect of the coastal erosion on risk assessment methodology, represented by means of a simple 1-line model based on Miller and Dean (2004).

Erosion model is based on the assumption that the starting shoreline position assumed in the calculations corresponds to the equilibrium position. Equation 4.3 is the governing differential equation:

$$\frac{dy(t)}{dt} = k * (y_{eq}(t) - y(t)) \tag{4.3}$$

where:

y(t) is the shoreline position at time t;

$y_{eq}(t)$ is the equilibrium shoreline position determined by forcing at time t;

k is the constant governing the rate at which the shoreline approaches the equilibrium.

Equation 4.3 shows that the shoreline approaches an equilibrium form at an approximately exponential rate. The differential equation is solved utilizing a numerical finite difference approach presented in Miller and Dean (2004).

Erosion model does not consider the presence of long-shore interruptions of sediment transport, such as jetties, marinas and groins. Therefore the methodology is suited for open coasts only.

THESEUS DSS allows end users to interact directly by providing a shape file of the eroded shoreline predictable, based on expert judgement and historical trends.

4.2.3 Modelling Coastal Ecosystems

Coastal ecosystems are under considerable additional pressure, due to the disproportionally large coastal population growth and development. Furthermore, sea-level rise presents a new threat, which combined with changes in the weather patterns, are likely to increase the vulnerability of coastal ecosystems to human-induced and natural stressors (Zanuttigh *et al.*, 2014).

The vulnerability of coastal ecosystems has been explicitly modelled as part of THESEUS Decision Support System, which considers the impacts of flooding on coastal ecosystems from both a short term and long term perspective. Impacts of floods are evaluated in relation to community and habitat vulnerability and also resilience to flooding, erosion and damage associated with storm events.

The most vulnerable ecosystems are the ones in which both resistance and resilience are low and the persistence of such systems is highly unlikely, especially unfavourable scenarios of climate change.

The ecological modelling carried out in THESEUS has developed an Environmental Vulnerability Index (EVI) for 10 coastal habitats. These habitats represent key coastal ecosystems across Europe that are also found within the THESEUS study sites and are considered to be at risk from flooding.

The types of habitat to be mapped in this DSS include:

i. Habitat extent: in the form of a habitat land use map, including both intertidal and terrestrial habitats, and appropriate shallow sub-tidal communities;
ii. Protected sites: sites designated for their ecological importance;
iii. Key species: including rare species and species protected under the Habitats Directive of European Commission (1992);
iv. Commercial important features: locations where economically important species are harvested;
v. Other important features: habitat features such as key breeding sites for birds or distinct habitat/land use related to study site.

The habitats (and key species) affected by flooding and erosion are considered as Receptors following the SPRC methodology (Narayan *et al.*, 2014). Hence they may change in the Sources as follows:

i. *Short-term processes* (storm surge, tides, wind driven waves);
ii. *Long-term processes* (sea level rise, vertical land movements – uplift/subsidence).

Short-term processes are temporary processes where after inundation, floodwater will subsequently retreat. In the other hand, for inundation due to *long-term processes* (sea-level rise) it is assumed that water will not retreat.

If habitats have the ability to "retreat" (the affected terrestrial habitats can move landward), making these newly occupied territories considered as additional coastal habitat.

To assess the vulnerability of ecosystems to changes an index is adopted within the THESEUS project. It provides a rapid and standardised method for characterizing vulnerability across coastal systems, and identifies issues that may need to be addressed.

Vulnerability of habitats is dependent on:

- Which part of a particular habitat area will be subject to the unfavourable impact and which species will be affected;
- The degree of sensitivity of habitats/key species to unfavourable impact/hazard.

The Environmental Vulnerability Index (*EVI*) proposed is similar to that used in Gornitz *et al.* (1994), Boruff *et al.* (2005) and. It is obtained through the square root of the product of the ranked variables divided by the total number of variables. The *EVI* ranked variables respond to the secondary Sources for particular habitats:

$$EVI = \frac{(A_1 \times A_2 \times \ldots \times A_n)^{0.5}}{n} \tag{4.4}$$

where:

A_1, A_2, ..., A_n are different receptor habitats/species, identified for the discrete area; and n is the number of different receptor habitats/species. An score of 0, 1, 2 or 3 is given for each habitat following Table 4.1.

Table 4.1 - Definitions of the Environment Vulnerability Index (EVI) (Zanuttigh *et al.*, 2014)

	EVI Index	
Negligible	0	Negligible impact to habitats species.
Transient effect	1	Changes within the range of Receptor's natural seasonal variation and full recovery are likely within a season.
Moderate effect	2	Changes are beyond Receptor's natural seasonal variation. Partial recovery is possible within several seasons, but full recovery is likely to require human intervention.
Permanent effect/change	3	Changes are so drastic that natural recovery of receptor is very unlikely without human intervention.

The assessment is done through the following steps:

i. Define sources: Sources are examined with respect to their potential to cause habitat degradation;
ii. Identify and map habitat types;
iii. Identify consequences of the source in each habitat receptor;
iv. Calculate the area affected;

v. Calculate the *EVI* for each habitat following Eq. 4.4.

Four categories are proposed for short-term and seasonal processes (categories 0, 1 and 2) and for long-term processes it is assumed that habitats will be permanently affected (category 3).

In the DSS, the estimation of *EVI* of a given habitat requires in turn the estimation of relevant parameters and this requires effort from both ecologists, who have to identify these parameters and their functional relation with the *EVI*, and coastal engineers, who have to schematize and evaluate these parameters (Zanuttigh *et al.*, 2014).

An example of the *EVI* is given on Table 4.2 for *Sabellaria Reefs* elaborated by the ecological team of THESEUS (Zanuttigh *et al.*, 2014). The *EVI* depends on the increased **wave action**, in terms of intensity and frequency, and on **sediment depth** and **duration**. The maximum value of the *EVI* has to be assumed after computing the values of the *EVI* based on threshold values of sedimentation and sea waves.

Table 4.2 – Example of *EVI* table for *Sabellaria* reefs (Zanuttigh *et al.*, 2014)

Sedimentation			
Quantity of sediment	Light	Medium	Heavy
Duration of sediment	<1 cm	1-10 cm	> 10 cm
Daily	0	1	1
Springs	1	2	2
One per Month	1	2	2
One per Year	2	2	SB
Every 10 years	SB	SB	SB
Every 100 years	SB	SB	SB
Wave Action			
Intensity of Storms	Slight	Moderate	Heavy
Frequency of increased wave action	10% increase	50% increase	100% increase
Daily	+	2	3
Springs	1	2	2
Once per month	0	1	1
Once per year	0	0	0
Every 10 years	0	0	0
Every 100 years	0	0	0

The sedimentation depth is estimated based on the typical annual wave climate and on Nielsen (1992) formula for sediment pick-up rate P:

$$P = 0.007W_s \left(\frac{t_b - t_e}{r(s-1)gD_{50}} \right)^{1.5} \tag{4.5}$$

where:

- W_s is the constant settling velocity of sediments;

- r is the marine water density;
- s is the relative density of sediments;
- D_{50} is the median beach grain size;
- t_e is the critical bottom shear stress for erosion;
- t_b is the bottom shear stress due to waves, and can be expressed as:

$$t_b = 0.5 \times r \times f_{2.5} \times U_w^2 \quad (4.6)$$

where:

- $f_{2.5}$ is a friction factor dependent on the grain size and calculated as $2.5D_{50}$;
- U_w is the near bed velocity due to waves, given as:

$$U_w = \frac{H_s}{2h} * (gh)^{0.5} \quad (4.7)$$

where:

- h is the water depth corresponding to breaking conditions for H_S.

The approximation of depth limited waves is considered and therefore,

$$h = \gamma_b \times H_s \quad (4.8)$$

Sediment re-suspension will be essentially driven by waves and the whole sediment deposition occurring during a typical average storm is fully re-suspended and drifted by currents within the storm duration S_d.

The typical **sediment deposition depth** *Sed_y* and **duration** *Sed_yd* are respectively given by:

$$Sed\_y = P \times S_d \quad (4.9)$$

and

$$Sed\_yd = S_d \quad (4.10)$$

where P is calculated based on the typical annual storm wave height.

The **wave action** is estimated from wave celerity, c:

$$c = \sqrt{gZ} \quad (4.11)$$

where

$$Z = Z_m T_r + Z_r(year) + H_s \times \frac{Tr}{2} \quad (4.12)$$

where T_r is the return period of the selected extreme events.

The selection of the return period T_r allows taking consideration of:

- The specific storm by means of Z_m and H_s, and therefore to represent the change in wave action within the same time slice (short, medium or long term scenarios);
- The time slice when dealing with sites where the waves are not expected to increase;
- The direct relation between c and P, Equation 4.5.

The increased wave action intensity is estimated as the variation of wave celerity c, considering the corresponding scenarios with the same T_r at the selected year and the present conditions, presented respectively by 'year' and '2010' in Equation 4.13.

$$\frac{[c(Tr, year) - c(Tr, 2010)]}{c(Tr, 2010)} \tag{4.13}$$

The increased frequency in wave action can be estimated if climate scenarios are available in the sites also for the typical annual wave climate.

4.2.4 Representation of Society

Social Vulnerability is a complex phenomenon and no single measure comprehensively covers the whole spectrum of such vulnerability (Adger *et al.*, 2004). Recently Social Vulnerability Index (*SoVI*) has been suggested as a comparative spatial assessment of human-induced vulnerability to environmental hazards (Blaikie *et al.*, 2014, Cutter *et al.*, 2003).

These *SoVI* is based on a large set of measurable variables that can be grouped into main common factors such as:

- population structure;
- gender;
- income;
- socio-economic status;
- renters.

Analysis and mapping of social vulnerability should also consider identifying critical facilities or resources to help prioritize potential hazard mitigation.

In the THESEUS DSS, social vulnerability is modelled considering two main aspects:

i. The damages to Critical Facilities (CF);
ii. The expect number of fatalities. Flood damages to society also include psychological consequences that are mainly qualitative in nature and are hard to be translated in linear functions with quantitative outputs for practical and ethical reasons (Tapsell, 2011).

Critical Facilities are defined as “the primary physical structures, technical facilities and systems which are socially, economically or operationally essential to the functioning of a society or community, both in routine circumstances and in the extreme circumstances of an emergency” (ISDR, 2009).

The impact of the flooding process on CF is estimated following three steps:

1. Ranking of Critical Facilities:

The rank used in THESEUS was based on the function of buildings in relation to social vulnerability. Considerations were made both in terms of use in emergency management and symbolic function. Approximated Social Value is ranked from 1 (low) to 5 (high), based on the damage degree of main facilities, Table 4.3.

Table 4.3 - Approximated Social Value (Zanuttigh *et al.*, 2014)

Approximated Social Value	Definition
1	Places which value is mainly symbolical, but can influence anyway the overall amount of social damages.
2	Facilities that provide public services but that are less critical for the community.
3	Facilities that provide important public services, main centres of aggregation, education or prayer and places that link those features with economics.
4	Facilities that provide significant public services and should be activated within 24 h, like nurseries, major water and sewer facilities, fire and police stations, schools and park facilities.
5	Critical structures that if involved could compromise the emergency action, the coordination chain, public safety and public health. They include hospital and emergency facilities, power plants and main military facilities.

2. Estimation of physical damage for structures

The damage scale is estimated based on flood depth and duration. Following the method by Schwarz and Maiwald (2008), the damage grade is related to the flood depth (De) through a non-linear function, Table 4.4. Effects on society and structures are inversely proportional to flood Duration (D). Long duration floods, even if relatively limited in space, produce greater impacts on social functions. Table 4.5 present the flood duration scenarios and the factor (D) adopted.

Table 4.4 - Factor flood depth (De) (Hodgson *et al.*, 2010, Schwarz and Maiwald, 2008, Zanuttigh *et al.*, 2014)

Factor De	Depth range
1	0.1-0.5 m
2	0.6-1.5 m
3	1.6-2.5 m
4	2.6-5 m
5	>5 m

Table 4.5 - Factor flood duration (D) (Zanuttigh *et al.*, 2014)

Factor D	Flood duration
1	Hour/s
2	Day/s
3	Week/s

3. Definitions of tourist impact

The geographic features that determine the social vulnerability are related both to the physical structures and to the situation where the action is settled (Cutter, 1996). Tourism and its presence should be considered one of the most relevant variables affecting the ordinary social pattern. Tourist presence is represented through a value reflecting seasonality S, where for low season S=1 and for high season S=2, Table 4.6, acting as a final scale multiplier.

Table 4.6 - Factor seasonality S (Zanuttigh *et al.*, 2014)

Factor S	Definition
1	Low seasonality
2	High seasonality

The Collateral Social Damages are estimated trough the following equation,

$$CSD = S_I ASV_i DeDS \tag{4.13}$$

The value of CSD is related to a common scale to allow exportability to other case studies and comparison of the results, Table 4.7.

Table 4.7 - Collateral Social Damage (Zanuttigh *et al.*, 2014)

Score	Definition
0	No collateral social damage.
1-10	The damage is limited and could be managed with experimented procedures and stakeholders activation.
11-20	Malfunctions in citizens' life are expected. The damage is limited but diffused (or high and very concentrated).
21-30	Social damages are concrete and visible. External help is suitable and should be activated in advance in order to avoid higher losses.
31-50	Massive social damages in ordinary period or medium involvement of critical infrastructure in high touristic period. External help is absolutely needed.
51-100	Exceptional damages, calamity. The situation could have terrible social damages and should be mediated with external help and cooperation at the highest level possible.

4.2.5 Economic Modelling

Economic Vulnerability Index (*EcVI*) derives from the composition of the following indicators (Guillaumont, 2009):

1. Population size;
2. Remoteness;
3. Merchandise export concentration;
4. Share of agriculture, forestry and fisheries in gross domestic product;
5. Homelessness owing to natural disasters;
6. Instability of agricultural production;
7. Instability of exports of goods and services.

In a Multi-Criteria Analysis, social and economic impacts must be distinguished and separately weighted, so the index turned out to be inadequate, since it combines social and economic indicators. Instead, since detailed data on economic activities in Gross Domestic Product (GDP) terms were available, a consistent approach based on incomes for each economic land use was adopted (Zanuttigh *et al.*, 2014).

Economic Consequences (EC) of flood in terms of flood depth and flood duration are estimated according to the following formula:

$$EC = v_{ij}\, b_j\, Fd + v_{ij}\, a_j \sqrt{Fy}$$

where:

- v_{ij} are the values of land uses in euro/m^2/year;
- Fd is the flood duration;
- Fy is the flood depth;
- a_j are proportionality constants for each land use j;
- b_j are proportionally constants that express the expected period to restore economic activities.

The land use value loss is combined with beach loss due to erosion. The value was derived from a choice experiment exercise carried out at the Santander site, ES, within THESEUS project distinguishing the Willingness To Pay (WTP) for bio-diversity, health risk and recreation.

Alternatively, a consistent approach based on market values of infra-structures could have been used. Note that it is theoretically possible to move from an income approach to an infrastructure approach under a standard set of assumptions about market competition (Zanuttigh *et al.*, 2014).

4.2.6. Multi-Criteria Decision Making

Multi-Criteria Multi-Expert Decision Making (MCMEDM) is a methodology to deal with the inherent complexity and uncertainty as well as the vague knowledge arising from the participation of many experts in the decision making process (Yan *et al.*, 2011).

In THESEUS DSS, issues related to vagueness or qualitative indexes were not examined, since each expert group reached an internal agreement on one or more quantitative indexes to be applied.

Multi-Criteria Decision Making (MCDM) is a response to the inability of people to analyse multiple streams of unalike information in a structured way: preferential information is modelled by weighting factors and value functions.

This methodology was applied in THESEUS framework, by weighting the three impacts (ecology, society, economy) according to stake-holders preferences or other user specified weights and by normalizing all values estimated by experts.

4.3. End User Involvement in THESEUS

4.3.1. Fundamentals of THESEUS DSS

THESEUS provides an integrated GIS-based methodology for planning sustainable coastal defence strategies, taking into account technical, social, economic and environmental aspects. It has been defined as a scoping tool to assess risk conditions and consequences of mitigation options against flooding and erosion.

This DSS enables the assessment of the change in risk due to a range of scenarios and selection of the most appropriate intervention measures of engineering, ecological and social measures.

Zanuttigh *et al.* (2014) mention that this DSS has as main foundation to be "Open and Parametric", both in terms of source code and technology and in terms of usability. It is also designed to be modified and distributed across many sites with many different characteristics, which usually require flexibility in terms of configuration and input materials.

The tool is also provided with 'Interactivity'. While being trained in interdisciplinary risk assessment, users can explore a combination of scenarios including the best (sustainable) solution or combination of solutions for risk mitigation. Sustainable is here defined as the protection of the coast while preserving its socio-economic development and the integrity of ecosystems (Zanuttigh *et al.*, 2014).

The limitations of the tool of THESEUS are listed above:

- Drivers, pressures, impacts and response options in different time slices are provided but is not expected to replace with detailed design tools;
- Gives implications of different policy decisions, but it does not prompt the selection of specific policies;
- Do not provide a straightforward decision since it does not overcome the representation of the social perception of risk and the resilience of society and does not include an uncertainty component in the both physical processes and consequences.

Figure 4.1 shows an overview of the structure of the integrated model at the most synthetic level.

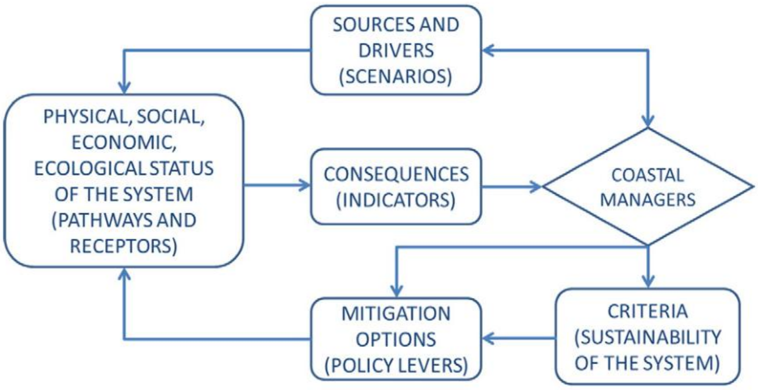


Figure 4.1 - Synthetic overview of the structure of the integrated model (Zanuttigh *et al.*, 2014)

4.3.2. Tool Design

The participation of the stakeholders brought important developments to the design of the tool namely to test the outcomes of the modelling, to identify the most relevant parameters and related scenarios to be included in the analysis and to evaluate adaptation options, stakeholders participation was of great interest.

Following, some of the inputs gave by the stakeholders to the utility of THESEUS DSS:

- Definition of the site boundaries;
- Identification of critical pathways of the existing coastal management that may lead to failure;
- Usefulness of output indicators for each of the meta-models;
- Site-specific relevance of the social, economic and environmental components at risk;

- Functionality and user-friendliness of the interface.

The set-up of the tool considered two key aspects:

i. Intuitive and interactive design of the Guider User Interface;
ii. Balance of simplified modelling assumptions and speed to promote the use of the tool for testing different combinations of mitigation options.

4.3.3. Type of Outputs

THESEUS DSS operates at high resolution to provide geographical specific outputs. Regarding scale, intermediate maps of specific results, as flood depth, land value loss, life losses are shown with their own scale while the results of hydraulic, social, economic and ecological vulnerability and the overall risk assessment are given as normalised-quantitative indicators (Zanuttigh *et al.*, 2014).

The start interface for each site consists of a "start view", Figure 4.2, where is possible to visualize the input data and evolves to the next four screens, each one with a different function:

i. **Definition screen** which allows the user to define the name of the test, write a short description or even load some settings of a previously performed analysis;
ii. **Scenarios screen** which allows the selection of climate, social, environmental and economic scenarios, Figure 4.3. The user can choose pre-set scenarios defined by the scientists or can create his own scenario by changing the input parameter values used in the models;

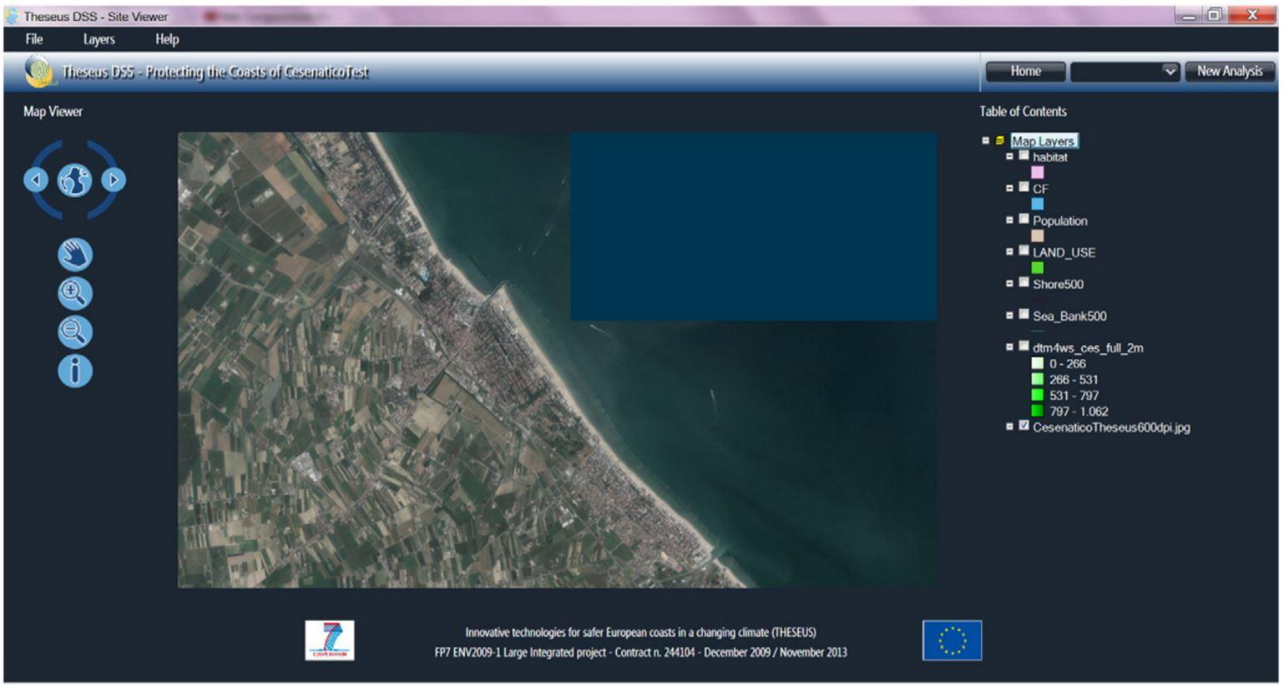


Figure 4.2 - The start view (Zanuttigh *et al.*, 2014)

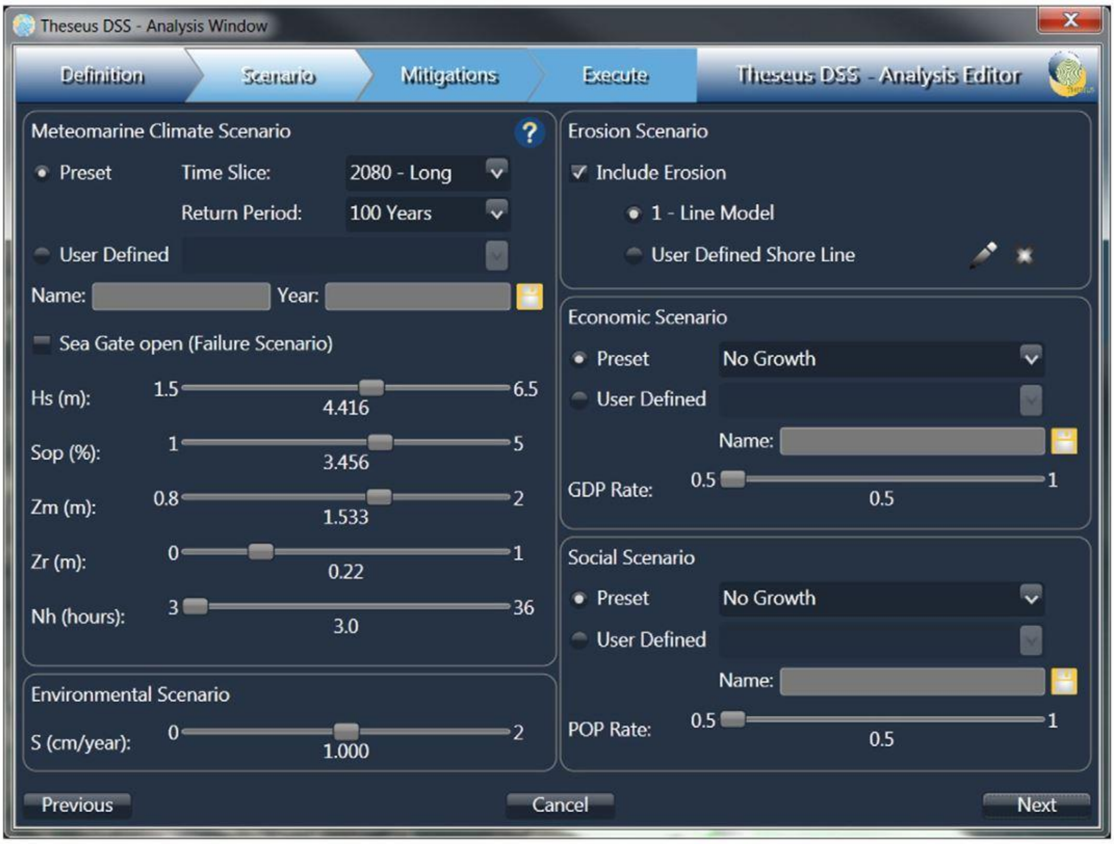


Figure 4.3 - Scenarios screen (Zanuttigh *et al.*, 2014)

iii. **Mitigations screen** (Figure 4.4) which allows the user to include:

1. **engineering mitigations** like wave farms, sea walls, nourishments, barriers, breakwaters;
2. **ecological mitigations** such as management or construction of dunes, biogenic reefs or salt marshes;
3. **economic and social mitigations** such as evacuation plans, land use change and zoning and insurance scheme.

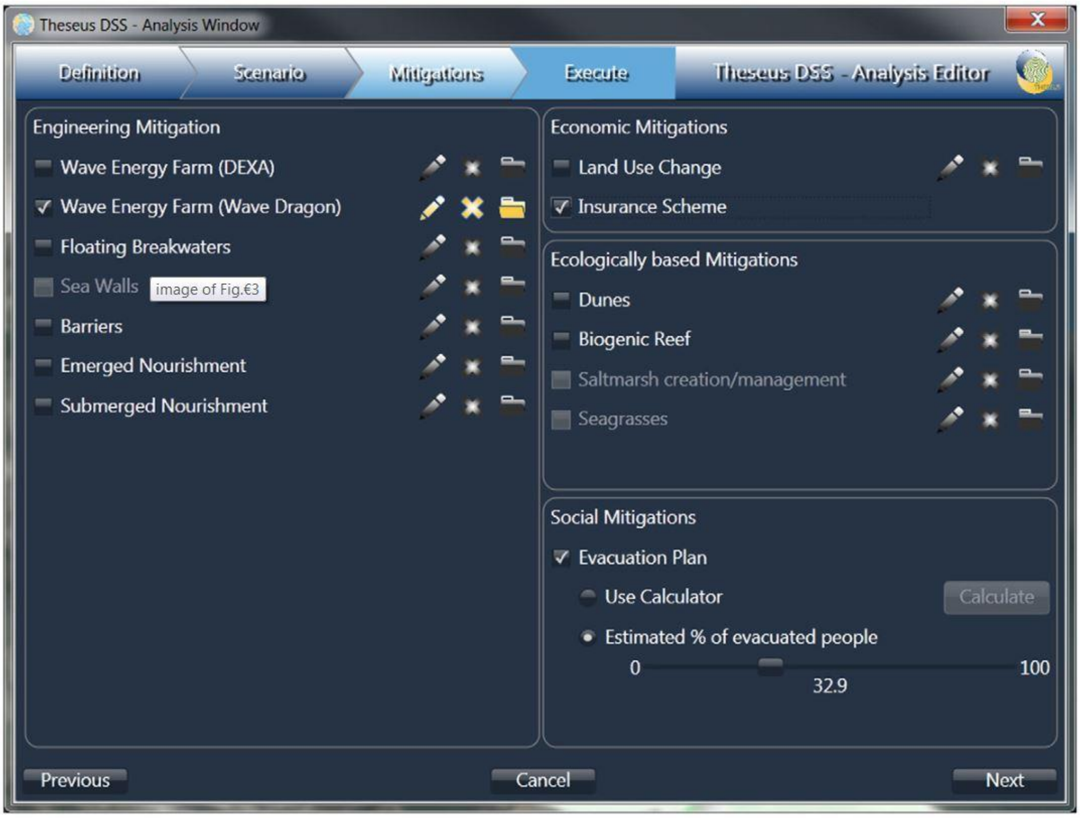


Figure 4.4 - Mitigations screen (Zanuttigh *et al.*, 2014)

When the user selects a mitigation option, he can include the shapefile prepared by the scientists with suggested configuration, upload a shapefile and enter the design parameters, or draw the mitigation directly on the software, Figure 4.5.

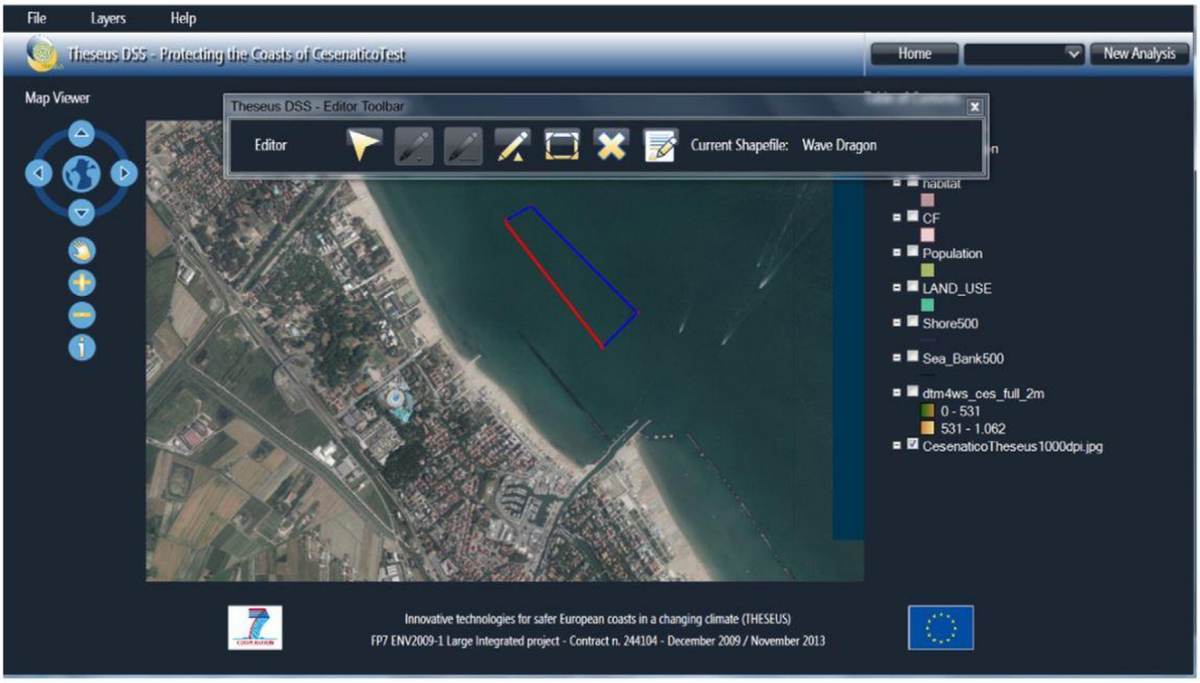


Figure 4.5 - Editing an engineering mitigation option in front of Cesenatico (Zanuttigh *et al.*, 2014)

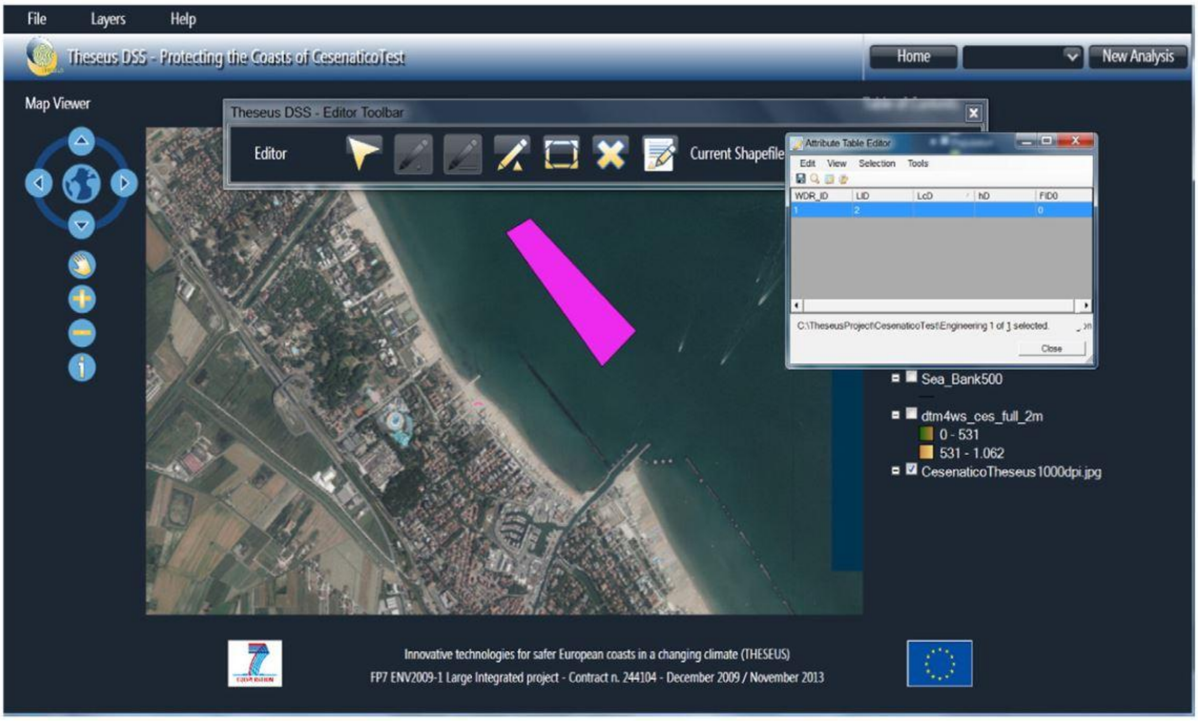


Figure 4.6- Editing an engineering mitigation option in front of Cesenatico (Zanuttigh *et al.*, 2014)

iv. **Execution screen** (Figure 4.7) which guides the user through the analysis to be performed based on options previously taken. The steps of the analysis are listed below:

1. modelling of the physical processes, erosion and flooding;
2. modelling the impacts on the environment, the society and the economy;
3. assessing the global hydraulic, social and environmental vulnerability;
4. assessing the risk.

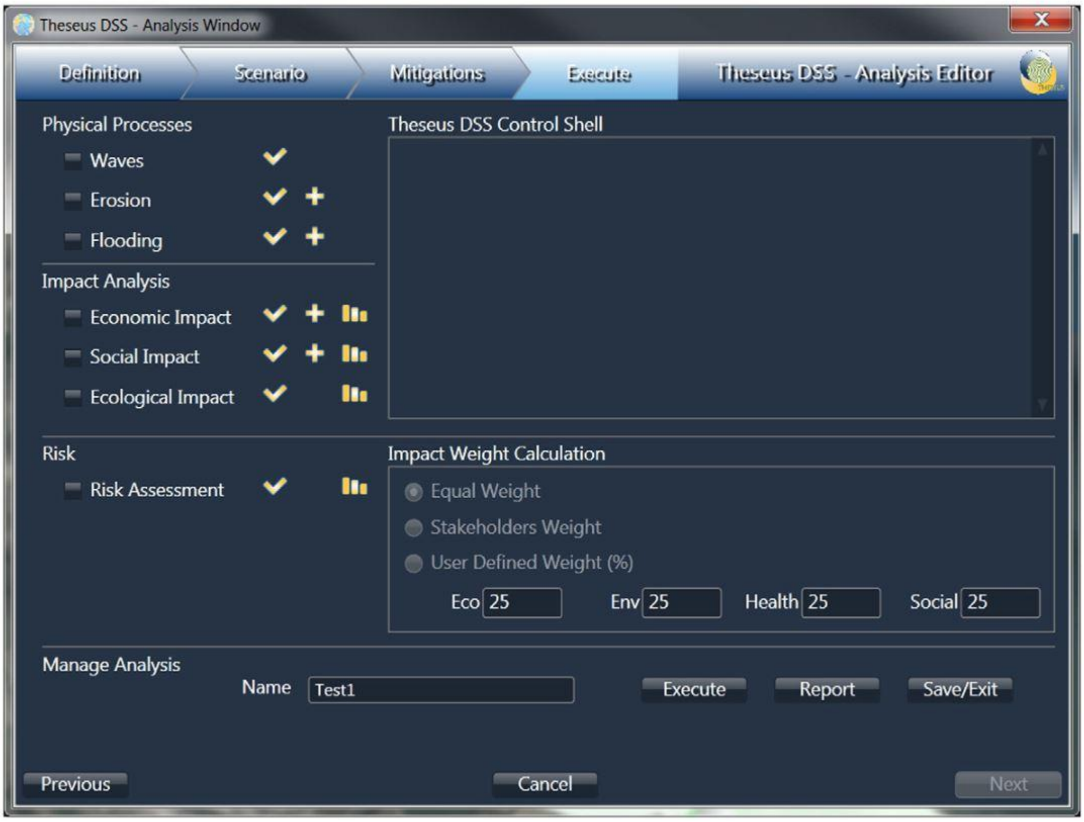


Figure 4.7 - Execution screen (Zanuttigh *et al.*, 2014)

4.4. TECHNICAL STRUCTURE

4.4.1. STRUCTURE

The structure of THESEUS DSS and the subsequent flow of information is represented in the next diagram, Figure 4.8.

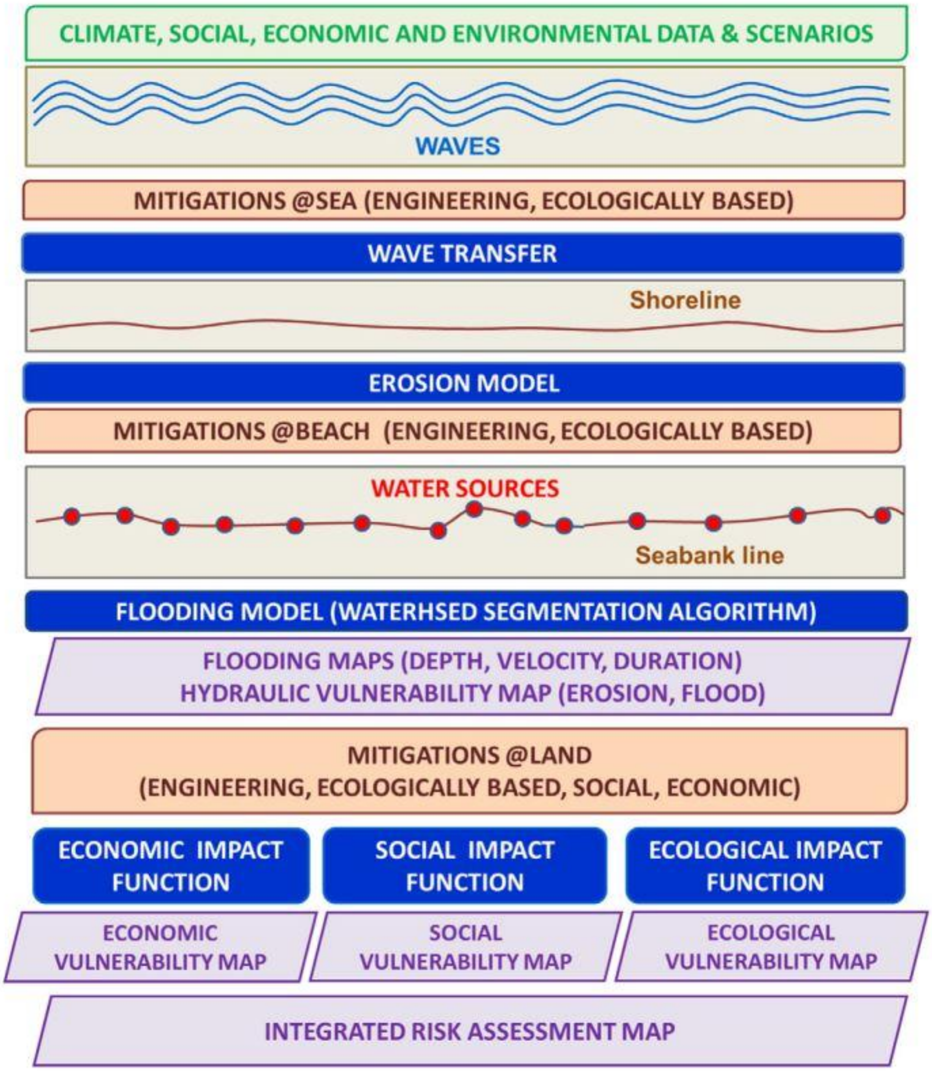


Figure 4.8 - THESEUS DSS structure and flow of information (Zanuttigh *et al.*, 2014)

Input data

The input data is the information that will describe the most the study site and in the case of THESEUS DSS, it should include:

- Digital Elevation Model (DEM);
- Hydraulic structures and infrastructures position;
- Geometry buildings and coastal infra-structures;
- Map of land-use (Figure 4.9) and of critical facilities;
- List of geo-referenced social and economic indicators (Figure 4.10);
- Geo-referenced maps of habitat types and species.

Furthermore, input data related with the study place include:

- Typical breaking index;
- Average beach grain size diameter;
- Beach slope;

- Water depth where wave data were obtained;

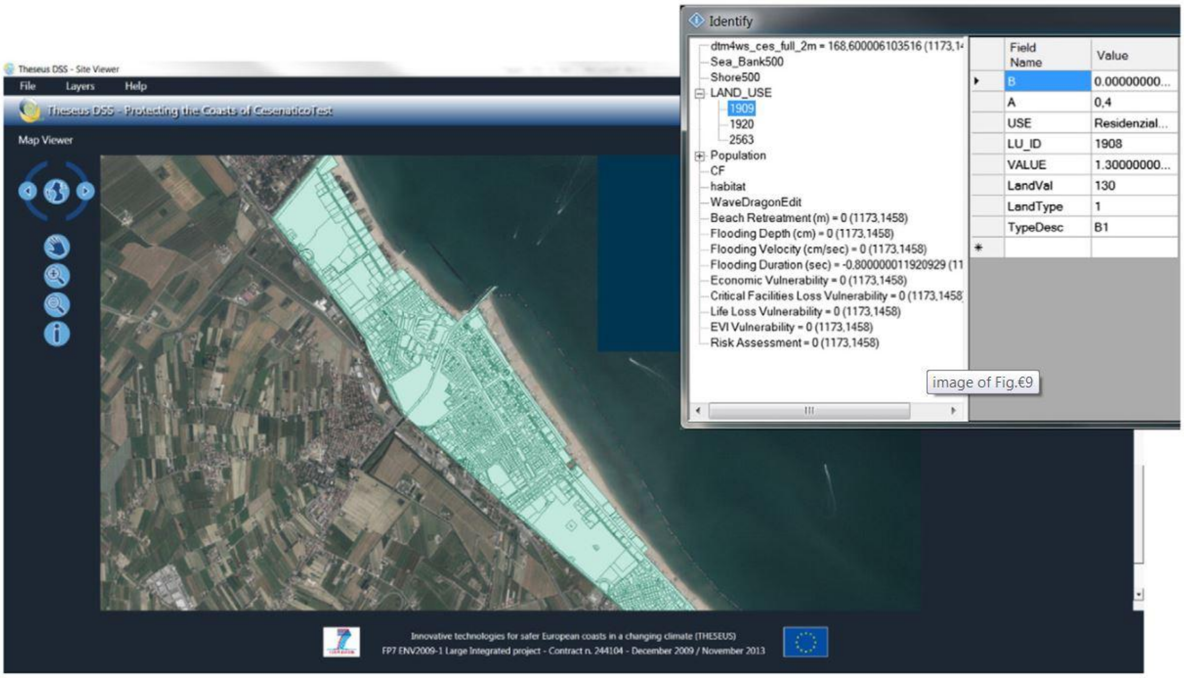


Figure 4.9 - GIS based map and information about land use (Zanuttigh *et al.*, 2014)

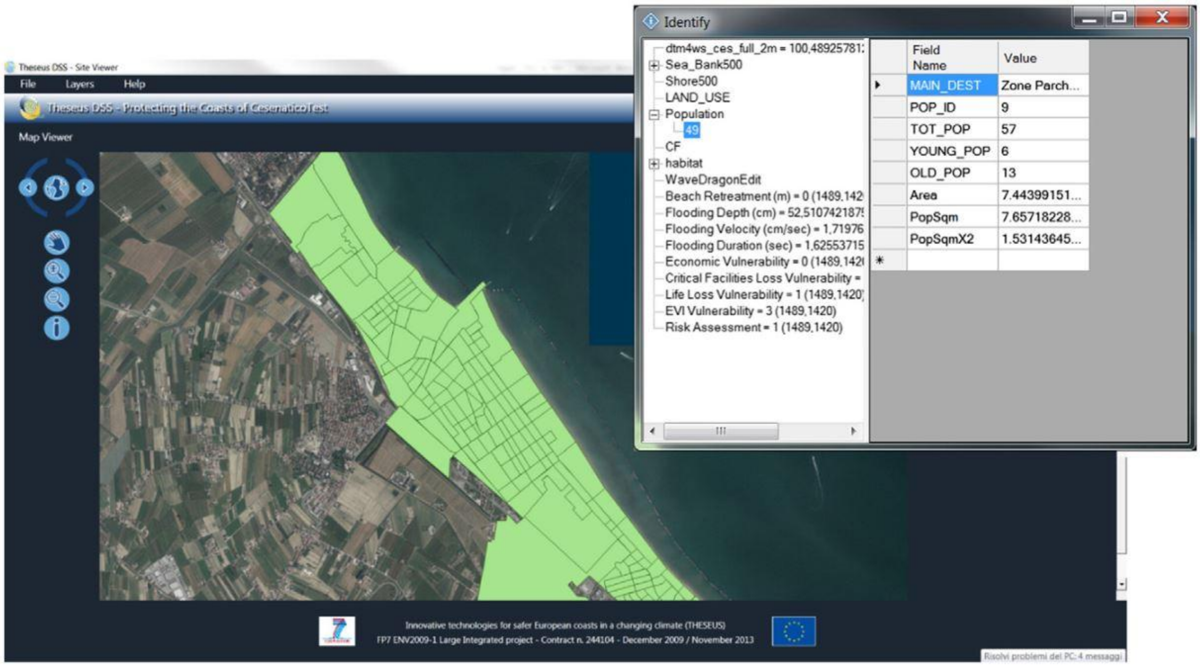


Figure 4.10 - GIS based map and information about population density and age (Zanuttigh *et al.*, 2014)

Scenarios

THESEUS DSS is based on the following scenarios:

- Climate and environmental scenarios, whether pre-defined set of conditions (storm surge, wave height, sea-level rise) derived by the researchers team or combination of intervals defined by the user;
- Economic and social scenarios, based on expected trends of the population and on the gross domestic product;
- Environmental scenarios;

Interconnecting Elements

The following elements should be defined in order to allow hydraulic modelling of the DSS:

- Waves: position of point(s) or line(s) for off-shore generation has to be identified based on the indication of the off-shore water depth;
- Shoreline and sea bank line; the lines represent the water/beach boundary relative to which beach retreat is determined;
- Water sources: punctual sources should be defined for the flooding initiation for each coastal segment.

Mitigation Options

Mitigation options are represented both as changes of pathways and of receptors (Zanuttigh *et al.*, 2014).

A farm of wave energy converter reduces wave energy and consequently acts on the pathway. This reduction of wave energy also reduces loadings on coastal structures and coastal erosion, which is observed in DSS as a modification of the wave heights.

Managed realignment fundamentally changes the land use but may also change elevation depending on how it's implemented. Within the DSS this expresses a change of the land use values and roughness for flood propagation.

A new dune raises the Digital Elevation Model and also creates a habitat that is relevant for coastal protection. In the DSS this is expressed as a modification of the digital elevation model and the habitat map.

Modelling Erosion and Flooding

The processes include wave transformation from off-shore to the shoreline, beach erosion, wave run-up on the beach and overtopping over the sea-bank, and flooding.

- The wave transfer from off-shore to the shoreline was done through a refraction model, as given by Gōda (2000);
- Computation of wave reduction due to engineering and ecologically based mitigations between the off-shore line and the shoreline by means of specific functions defined with THESEUS OD 2.7 (THESEUS, 2013);
- Estimation of the shoreline change induced by the storm through the calculation of Equation 4.3;
- Estimation of wave run-up on the beach from Equation 4.2;

To estimate the consequences of flooding into society, economy and ecology, it is necessary to obtain the maps of flood duration and flood velocity. To obtain the map of flood duration it is needed to combine the Darcy law regarding water percolation, with the mass balance in the surrounding flooded area. The map of flood velocities (Figure 4.11) is derived by applying the generalised Bernoulli's theorem between paired points along transects normal to the shoreline (Zanuttigh *et al.*, 2014).

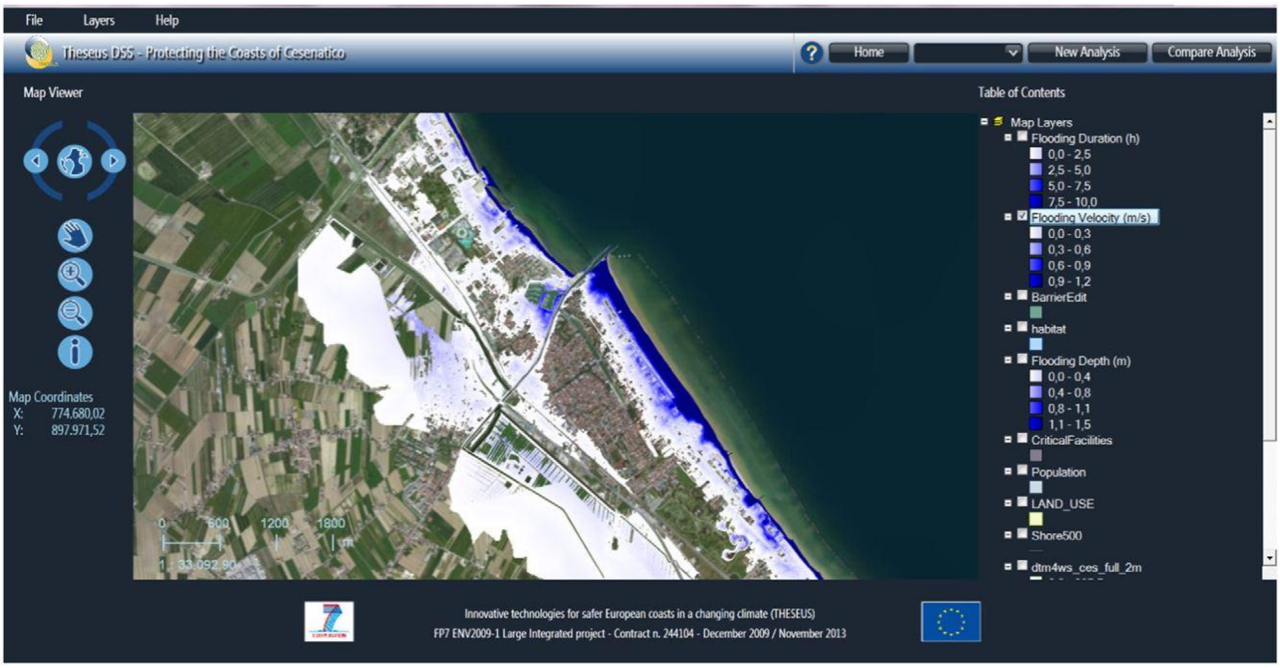


Figure 4.11 - Map of flooding velocities for the long term scenario with return period of 100 years (Zanuttigh *et al.*, 2014)

Consequences, Vulnerability and Risk Maps

THESEUS team developed impact functions to link economic, social and ecological data to hydraulic parameters (beach retreat, flood depth, flood duration and flood velocity). These functions allow to obtain the maps of the consequences, whether social, economic and ecological (Zanuttigh *et al.*, 2014).

Economic losses are divided into the losses in the urban area and into the beach. In the urban area the losses are represented as €/m^2 and in the beach area as €/m.

Social losses are expressed as two types of percentages: number of expected deaths of the local population in the area and functionality loss of each Critical Facility (Figure 4.12).

To obtain a scale from 1 to 4 of the impacts it is necessary to develop a normalisation procedure. This procedure is realized by dividing the local values of the consequences by the corresponding site-specific thresholds. These site-specific thresholds are obtained by comparing the consequences of different scenarios with historical experience and data available in the site.

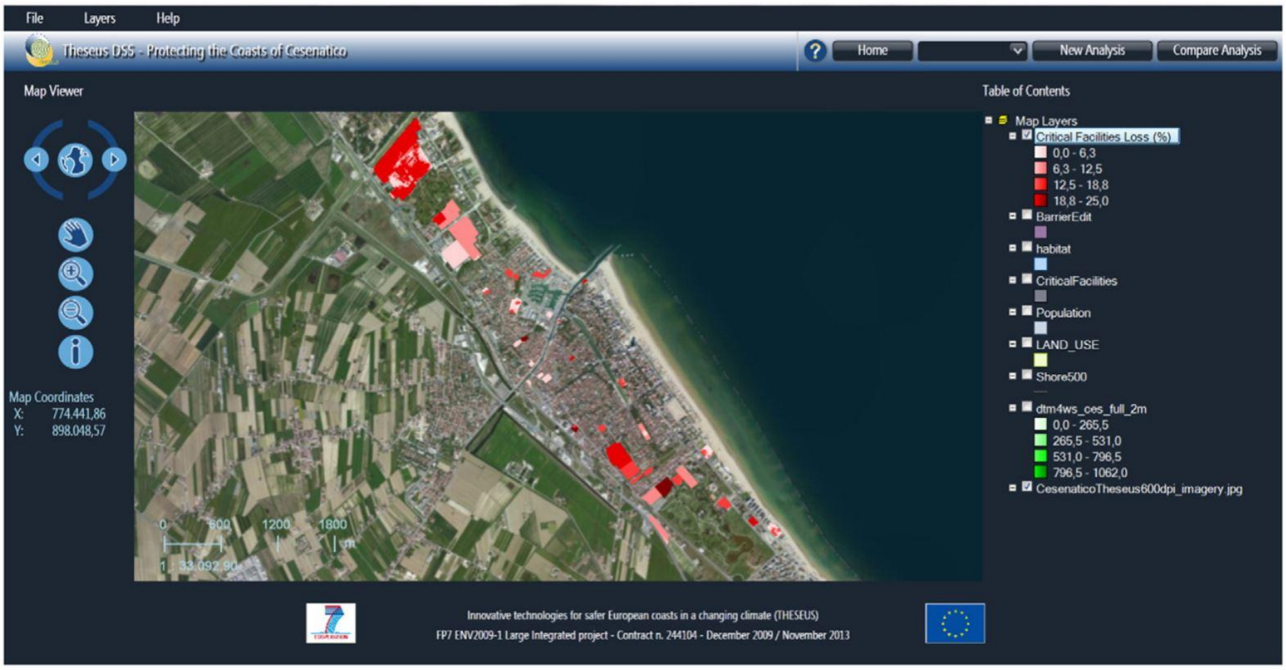


Figure 4.12 - Impact on critical facilities expressed in percentage (Zanuttigh *et al.*, 2014)

Ecological vulnerability map is derived from the calculated values of the Environmental Vulnerability Index, by associating the *EVI* 0-3 scale to the 1-4 vulnerability scale. Hydraulic, social and economic vulnerability maps are obtained, being the vulnerability assessed as:

Vulnerability = Exposure = - Resilience

where exposure is the value at risk (de Vries, 2011) and resilience is the damage that will not alter the main functions of human and physical systems in equilibrium in discrete times and at local scale (De Bruijn, 2004).

This set of definitions was adopted as a result of the integration of the different ways THESEUS scientists conceive risk depending on their specific background (Zanuttigh *et al.*, 2014).

Hydraulic vulnerability map is derived from a weighted average of the maps of flood depths, velocities and durations. **Economic vulnerability map** is obtained by a spatial combination of the normalised beach losses and the normalised inland value loss. **Social vulnerability map** derive from a combination of the normalised maps of life losses and CF losses.

In order to obtain the risk map, these vulnerability maps are combined through a weighted procedure, Figure 4.13. To the generation of the risk map, users can select equal weights, their own weights or the ones resulted from the surveys at the study sites.

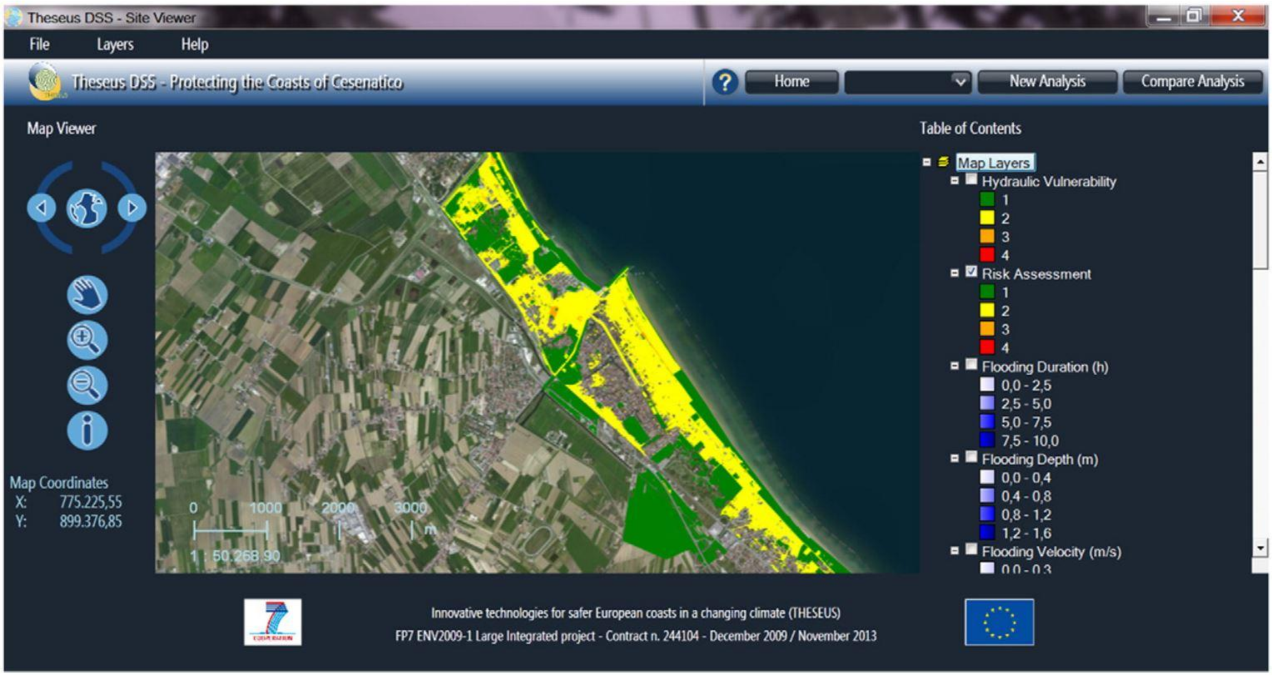


Figure 4.13 - Example of integrated risk map (Zanuttigh *et al.*, 2014)

Technological Framework

The desktop-based architecture of THESEUS DSS consists of three main components (Zanuttigh *et al.*, 2014):

- Set of windows forms that allows the user to interact with the system - GUI;
- GIS-based that add spatial capabilities to the system;
- Final tier for the integration of models.

The technological framework selected for the THESEUS development was the Microsoft.NET 4.0, so the DSS can be run on any Microsoft Windows PC. The NET Framework includes a large class library for data access, user interface or network communications.

The GIS components of THESEUS DSS were accessible through the open-source set of libraries of DotSpacial. This software is capable to work with common GIS files such as ESRI Shapefile.

4.5. Challenges and Limitations of the THESEUS DSS

The conceptual approach and the simplified modelling assumptions may be considered too simplistic by the coastal managers and stakeholders to trust the reliability of the results.

Topographic, social, economic and ecological high spatial resolution data that are required to run the DSS may be not available.

The non-linear interdependence of the mitigation options is not considered.

Risk perception and social resilience and its effects in terms of preparedness and social changes in terms of cohesion, livelihoods and opportunities are not considered. It was not considered a cost-benefit analysis.

4.6. CONCLUSIONS

Within THESEUS project it was possible to provide coastal managers with information about present and future flood risk assessment and support sustainable long-term planning of mitigation options.

The tool is based on a series of linked models to allow rapid run-time and quick response to the user. In the preliminary risk assessment phase it identifies the most threatened areas while in the preliminary planning phase it verifies the most promising mitigation options.

The Decision Support System is open source and parametric so that it can be applied to any coastal are independent of scale issues. It requires appropriate site data to simulate inundation with great accuracy (DEM) and to represent social and economic vulnerability.

The tool is able to allow the user step by step interaction by setting up scenarios, selecting mitigation options and changing weights within the multi-criteria risk analysis. The possibility to run and compare different conditions allows the users to explore flood risk and to develop an impact-oriented approach to coastal risk mitigation (Zanuttigh *et al.*, 2014).

5
CONCLUSIONS

5.1. An Overview of the Content

This thesis has been developed to inform and describe some of the methodologies utilized for vulnerability and risk assessment. It was understood that they started be elaborated in the late 1980's and have been gaining detail since they are taking account more quantitative data, and also trying to give better adaptation and sustainable strategies for coastal managers.

The second chapter of this work was done having in mind which subjects should make part of an introduction to this field of knowledge.

As evidenced globally, coastal zones offers several conditions for the settlement of populations and development of their main activities. However, this environment is suffering from ocean dynamics and climate change consequences. The major impacts are associated with permanent inundation of low-lying areas, increased flooding due to extreme weather events (e.g. storm events), and greater erosion affecting beaches and cliffs.

It was concluded after analysing the major impacts or **risks** related with coastal hazards that the analysis of these impacts the evaluation of two main components: **hazard** (an event or phenomenon with the potential to cause harm such as loss of life, social and economic damage or environmental degradation; **system vulnerability** (the characteristics of a system that increase its susceptibility to the impact of climate-induced hazards).

Vulnerability is also defined as a combination of physical, environmental, social and economical factors, whose assessment implies the integration of multiple qualitative data. Vulnerability parameters or indicators can be quite useful in a first assessment of vulnerability of different coastal parcels to different sea manifestations. They range from geophysical characteristics of the coastline to the local sea dynamics.

Risk concept has a great variety of definitions, however one of the most accepted ones in this context is the product of probability of occurrence of a given unwanted event by the severity (consequences) associated.

The assessment of levels of risk is essential to prioritize some high vulnerable areas where action is needed. This task should be divided in three stages: risk identification, risk analysis and risk evaluation. When, in these vulnerable areas, populations have fixed for living and establish their activities, risk arises, consequence of the presence of livelihoods.

The state of the art/bibliographic review, done in the third chapter identify an progressive upgrade on the specifications of the methodologies (which term is also use to refer tolls, techniques, and different methods) of analysis of vulnerability and risk. This methodologies were grouped according their type of analysis, referencing the scope, approach, complexity and application scale.

The generic approaches of coastal vulnerability analysis are used as initial, baseline analysis for country based studies where almost no investigation is done.

The Intergovernmental Panel on Climate Change release the Common Methodology in 1991, and it was developed to assist countries in making first-order assessment of potential coastal impacts and adaptations to sea-level rise. Studies based on this methodology have served as preparatory assessments, identifying priority regions providing a first screening of possible measures.

The United Nations Environmental Programme published an Handbook on methods for impacts assessment and adaptation strategies, based essentially on a combination of widespread experience using the Common Methodology and other methods for coastal vulnerability assessment, which have been developed in response or addition to the CM. UNEP handbook is not intended to be prescriptive as to the use of scenarios or methods to be applied for the assessment of impacts and adaptation options. Instead, it advises users to select those scenarios and methods that are most appropriate for their specific situation.

These kind of methodologies are also a framework for developing more advanced studies.

The second group of methodologies that this work presents are the techniques and simple methods for describing and evaluating vulnerability and risk on the coastal zones.

AVVA is a technique for describing vulnerability of the coastal zones through aerial observation and record of the coastal geomorphologic and topography aspects. Is adapted from regional to national scale analysis however it could be used to describes small local changes on the shoreline.

SMART is a method that could be applied for the quick calculation of risk.

Coastal Zone Simulation Model (COSMO) was one of the first attempts to develop a decision support system to evaluate management strategies under different scenarios. Its main use is as a tool to help coastal managers to determine the advantages and disadvantages of adaptation strategies. It's not suitable to be applied alone; instead it should be integrated within frameworks such as UNEP or in conjunction with more quantitative data.

Index-based methods are the third group of this list and it is a well known and largely applied globally method for making assessment of different coastal segments. It is of easy implementation and are based on the analysis of past data (geomorphic cartography , tide gauge data, land use and socio-economic data) without requiring the use of numerical model projections or of adaptation scenarios. Coastal Vulnerability Indices and other variants of these group derived from the work of (Gornitz and Kanciruk (1989)) and it can be used at different spatial scales (local, regional and supra-regional) based on available datasets. Index-based methods are not immediately transparent since the final computed indices don not allow the user to understand the assumptions and evaluation that led to its calculation, and therefore a clear explanation is necessary to support proper use of methods.

The other group of methodologies the was identified are called the methods-based on dynamic computer models and they are divided into sector and integrated assessment models.

Risk Assessment of Coastal Erosion was a probabilistic assessment of the hazard and risk of coastal erosion in the UK, and it is considered innovative for the assessment of probability of failure of coastal defence, natural erosion rates and rates of uncertainty. RACE, like other sector models focusing on specific coastal process (i.e. coastal erosion in case of RACE) can be useful to support detailed assessment of specific vulnerability aspects. Up to now, this methodology has been specifically developed to assess hazard and risk of coastal erosion from local to national scale.

SimCLIM is an integrated assessment model, that has some promising features. It has a user-friendly interface and quick running software, which can run a variety of geographic and temporal scales for impact and adaptation assessment, it is flexible in generating scenarios and examining uncertainties and allows the user to examine climate variability and extremes as well as long-term change (Mcleod *et al.*, 2010). Unfortunately, the use of this software modelling system requires medium to high expertise for its customization to new regions.

DIVA can properly support coastal vulnerability assessment from global to national level, addressing various key coastal impacts and including selected adaptation strategies in the analysis. It has already been applied worldwide and its possible future development will likely to improve essential features like: higher resolution segmentation of the coastline; application at the regional sea scale, further exploration of patterns of sea-level rise and land subsidence and further adaptation options and strategies.

GIS-based Decision Support Systems, the last group of methodologies presented, support decision makers in a sustainable management of natural resources and in the definition of mitigation and adaptation measures.

The local to regional GIS-based DSS DESYCO enables the investigation of multiple climate change impacts on coastal areas. It is considered a flexible tool allowing the identification of vulnerability priorities and is able to deal with the analysis of uncertainty related to data input and resulting output. Main current limitations are related to the limited availability of well differentiated test areas, in particular at the European scale (Ramieri *et al.*, 2011).

After analysing superficially the progress and evolution of these methodologies, the remain objective of this master thesis was to describe with further detail the new open-source Decision Support System, developed within THESEUS Project.

This recent tool was developed to help coastal managers to design sustainable coastal protection strategies through the assessment of risk, selection of appropriate mitigation options in a integrated way (accounting for technical, social, economical and environmental aspects while considering short, mid and long term scenarios and the issues posed by climate change.

5.2. Final Considerations

Within the development of this master thesis, it was verified that the so called methodologies for vulnerability and risk assessment have focused mainly on the consequences of climate change, namely the sea-level rise,

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